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Sørensen, Lene

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Evaluation of Integrated Environmental Models A Case Study

Risø-R-732(EN)

Lene Sørensen

Risø National Laboratory, Roskilde, Denmark
March 1994

Abstract This report addresses the problems concerning the evaluation of Integrated Environmental Models. For purposes of clarity, the RAINS model developed at the International Institute for Applied Systems Analysis, Laxenburg, Austria has been examined.

The RAINS model is one example of an Integrated Environmental Model utilised on an international European level in the work on regulating the emissions causing acidification of the European environment. The model is described from a technical angle by going through its structure, modules, and submodels. Additionally, examples are given on how RAINS is utilised in various studies and in the international negotiations. Four other models also addressing the acidification problems are briefly described to provide a necessary basis for evaluating the RAINS model.

A sensitivity analysis has been applied to parts of the RAINS model. This analysis was focused on the so-called costs part of the model where a description of the economic considerations on emission reductions are sought. Through a conventional sensitivity analysis, the effect of changing various parameters on the cost results were studied. The analysis did not reveal any surprising conclusions about the sensitivity of the various parameters.

Finally, different criteria have been suggested and discussed on which to base the usability of the evaluation of the Integrated Environmental Models. These criteria are closely connected to the so-called Decision Support Systems. The criteria range from the evaluation of accuracy and robustness to that of simplicity, adequacy, and transparency of the model as a whole. Furthermore, consideration must be given to the effectivity of the model in accordance with how it contributes to solving a certain problem. The criteria are concretisised by applying them to the RAINS model.

From the analyses and experiences gained from working with the RAINS model, it can be concluded that the model is a scientifically sound one based on comprehensive work. More generally, it can be concluded that the fragmented analyses that are performed as a part of traditional model evaluation have their limitations. These analyses are insufficient to insure that the Integrated Environmental Models end up with a sufficient level of credibility so they can be used in decision and policy making. There is a need for widening the traditional concept of model evaluation so that aspects that are directed to the use of the model enter in. Finally, the study ends up with expressing the need for methodological approaches for performing these kind of evaluations.

The present report represents the third part of the Ph.D. dissertation "Environmental Planning and Uncertainty" submitted to the Technical University of Denmark, Lynby, Denmark. The defence took place 17 November 1993.

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Grafisk Service, Risø, 1994

Abstract (in Danish) Denne rapport omhandler problematikken omkring model-evaluering af integrerede miljømodeller. Konkret er der taget fat i en integreret miljømodel nemlig RAINS-modellen, som er udviklet på International Institute for Applied Systems Analysis, Laxenburg, Østrig.

RAINS-modellen er et eksempel på en integreret miljømodel, som anvendes på internationalt europæisk niveau i bestræbelserne på at regulere emissioner, som bidrager til forsuring af det europæiske miljø. Modellen beskrives ved gennemgang af dens struktur, moduler og undermodeller set fra en teknisk synsvinkel. Ligeledes er der givet eksempler på, hvorledes modellen anvendes i forskellige studier og i de internationale forhandlinger. Fire andre modeller, som også fokuserer på løsning af forsurings problemerne, er kort beskrevet for at give et sammenlignende grundlag for vurdering af RAINS-modellen.

En sensitivitetsanalyse er blevet udført på dele af RAINS-modellen. Denne analyse har været fokuseret på den såkaldte omkostningsdel af modellen, hvor man forsøger at give økonomiske betragtninger for emissionsreduktioner. Der er anvendt en konventionel sensitivitets analyse, hvor forskellige parameterændringers indflydelse på omkostningsresultater er blevet studeret. Analysen gav ingen overraskende konklusioner mht. til de forskellige parametres sensitivitet.

Sluttelig er der diskuteret og foreslået forskellige kriterier til at vurdere integrerede miljømodellers anvendelighed for beslutningstagere. De forskellige kriterier er tæt knyttet til begreber, der er familiære for de såkaldte Beslutnings Støtte Systemer, og spænder fra vurdering af nøjagtighed, og robusthed, til vurdering af detailjeringsniveauet, sprogbruget, og tilgængeligheden af modellen som helhed. Derudover er effektiviteten af modellen i relation til problemet, der skal beskrives, en faktor, der skal tænkes på. Disse kriterier er konkretiseret ved at anvende dem på RAINS-modellen.

Udfra analyserne og erfaringerne ved at arbejde med RAINS-modellen kan det konkluderes, at modellen er en videnskabelig sund model baseret på et grundigt arbejde. Mere generelt kan det konkluderes, at de fragmenterede analyser, der udføres som en del af en modelevaluering, har deres begrænsninger, når man følger de traditionelle punkter i model evaluering. Analyserne, som de fremstår, er ikke tilstrækkelige til at sikre, at de Integrerede Miljømodeller endeligt fremstår med et niveau af pålidelighed, så de kan anvendes i politisk beslutningstagen. Der er et behov for at udvide det traditionelle modelevalueringsbegreb, så også aspekter, som er direkte relateret til brugen af modellerne, indgår. Sluttelig ender studiet med at udtrykke behovet for metodemæssige aspekter til at udføre disse modelevalueringer.

Nærværende rapport repræsenterer tredie del af ph.d.-afhandlingen "Miljøplanlægning og Usikkerhed", som er blevet udført ved Danmarks Tekniske Højskole, Lyngby, Danmark. Forsvaret foregik den 17. november 1993.

Contents

Preface

This report addresses the problem of the evaluation of Integrated Environmental Models. One such model, the RAINS model, is described. The model has been the basis for a sensitivity analysis performed on parts of the model and for discussions on criteria on which to base an overall model evaluation for models of this kind.

The report forms the third part of a Ph.D. dissertation on "Environmental Planning and Uncertainty". The present report shall be seen as one of two case studies performed as part of this dissertation. The report can be regarded as an individual report but since at the same time it is a part of the whole dissertation, cross-references are made to the other parts of the dissertation in order to avoid too many repetitions. It is my hope that this does not affect the readability of the present report.

The work has been performed partly at Risø National Laboratory, and partly at a nine-months stay in 1991 at the International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria. I am especially indebted to the people in the Transboundary Air Pollution Project at IIASA for making the stay pleasant, inspiring, and very fruitful in terms of this work. Particularly, I am grateful to Markus Amann for his guidance and patience.

Additionally, I will thank the Danish Research Academy for making the stay at IIASA possible.

Roskilde, March 1994

Lene Sørensen

1 Introduction

One key issue in both environmental scientific environmental research and policy management is the credibility of mathematical models and information derived from them. Until now, this credibility has mostly been addressed in the scientific research context through comparisons of model output with observations, sensitivity analyses of selected parameters, various uncertainty analyses, and other model testings. Without doubt, these testings (under one referred to as model evaluation) are necessary factors in documenting a model. The question is whether these tests are sufficient to secure that the models are accepted and utilised as a tool in environmental decision and policy making.

The present report addresses the concept of model evaluation of the Integrated Environmental Models which are purposefully developed to be used as support for environmental decision making. It is the overall goal of the present report to widen the traditional concept of model evaluation so aspects of how the model applies to its users also are considered.

The case study takes its starting point in one Integrated Environmental Model, the socalled *R*egional *A*cidification *IN*formation and *S*imulation (RAINS) model. This model is one example on an Integrated Environmental Model which is actually applied to the European international negotiations on emission reductions (– the emissions causing acidification problems in all of Europe).

The RAINS model is a throughgoing theme in this report. The model is described, analysed in terms of a sensitivity analysis, and used as a basis for formulating some criteria to be considered when evaluating Integrated Environmental Models. The criteria focus on enhancing usability of these models and applicability in environmental decision making.

The present report has the following outline:

Chapter 2 presents the RAINS model in terms of aim, structure, and scope. The model is presented by going through its modules and submodels, and by this seeking to give an idea of how it can be used. As another part of presenting a model, four similar models are shortly described and compared to the RAINS model. Finally, this chapter gives examples on the usage of the RAINS model.

The model was analysed in terms of parameter sensitivities. Results of this study are given in *Chapter 3*. The test was based on a conventional sensitivity analysis applied to calculations of costs of emission abatements. This basically implied that three but highly linked cost calculations/results were considered, namely, cost coefficients, cost curves, and optimisation results.

In *Chapter 4*, the concept of model evaluation is taken up. Based on experience with the RAINS model, six criteria for evaluating Integrated Environmental Models are suggested. The RAINS model is discussed critically from these criteria.

The partial conclusions of the report are summarised in the conclusions section of *Chapter 5*. Additionally, this chapter discusses some open problems arising form the case study.

Two annexes are also available in the report. *Annex 1* describes the overall aspects and terms of the so-called acidification problem as it is addressed by the RAINS model. *Annex 2* consists basically of data which documents the results of the sensitivity analysis described in Chapter 3. Due to the large amount of data, only documentation data for the results directly reported upon are given.

2 The RAINS Model

Just prior to the United Nations Conference on Human Environment held in Stockholm 1972, discussions began on the problem of long-range transport of air pollutants. In April the same year, eleven European nations within the OECD agreed on initiating a programme to monitor and assess the long-range transport of air pollutants. Seven years later, findings of the survey were published: It was reported that a significant fraction of a single country's emissions of sulphur dioxide was transported hundreds of kilometres and deposited in other countries. Recognising that the scope (in geographical terms) of this study was insufficient for a full understanding of the causes and effects, the UN-ECE, which includes all of Europe, Canada, and the USA, took over the administration and discussions. As an immediate result, a conference on Long-Range Transboundary Air Pollution was convened by 32 European countries, EEC, Canada, and the USA. The resulting convention was ratified in 1983 by 24 signatories to limit and gradually reduce air pollution, in particular sulphur compounds.

At the end of 1983, the United Nations Environmental Programme, UNEP, financed the Co-operative Programme for Monitoring and Evaluation of Long-Range Transmission of Air Pollutants in Europe (EMEP). The World Meteorologic Organization cooperated with the EMEP network. The aim of the network was to develop a data base of concentrations and depositions of air pollutants, and provide information for validating computer models describing the long-range transport of pollutants. Currently, the Programme has 92 monitoring stations in operation within 24 European countries. EMEP represents today internationally a strong profile on the transboundary transport of air pollutants in Europe, and results of the programme are easily accepted as starting points in negotiations by most European countries.

Also in 1983, development of the RAINS model was initiated. The International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria was given the job of providing information on the atmospheric linkages between pollution sources and receptor sites to be included in cost-effective policy strategies discussed under the convention.

In 1985 a protocol was added to the convention. Before 1993 the 21 signatories of the protocol should reduce the total national sulphur emission level by 30% relative to the 1980 level (called a flat rate policy). Plans for similar protocols on nitrogen and ammonia were expressed.

Today, a protocol on nitrogen emissions exists, and the sulphur protocol is currently being renegotiated. International negotiations now focus on identifying alternative cost-effective strategies to the flat rate strategies leading to a widening on the view on the energy structure of the various countries, economic limitations, technical level, fraction of total emission, and the meteorological relationships to the receptor areas.

The RAINS model has been modified and changed continually, and is currently utilised as a tool in these analyses and negotiations. The subsections below present the model. The description is strongly based on Alcamo *et al.* (1990) where a more comprehensive documentation of the model can be found. However, there will be some deviations from this description since a new version of the model (numbered 6.0) was released in 1991. In some respects this version significantly differs from previous ones (as described in Alcamo *et al.*, 1990) and comments related to the new version are based on the author's experience and the RAINS manual.

It should be mentioned that the concept of Integrated Environmental Models is described in Sørensen (1993a).

2.1 Aim, Structure, and Scope

The purpose of developing the RAINS model was twofold: it was intended to gather existing scientific knowledge and provide an overview on causes and effects of acid deposition; it was also planned that it collect relevant statistics for characterising and describing these processes. This information was then intended for use in international discussions on identifying European policy strategies to diminish harmful effects of air pollution.

This was all done through a systems analysis approach where aspects of natural science, technique, economy, and policy options were combined in developing an Integrated Environmental Model.

The model comprises four more or less individual modules each divided into one or more submodels. A schematic presentation of the structure of the model can be found in Figure 2.1. The modules are: the Energy/Emissions/Costs and Agriculture Module, Critical Loads Assessment Module, Environmental Impact Module, and Optimization Module.

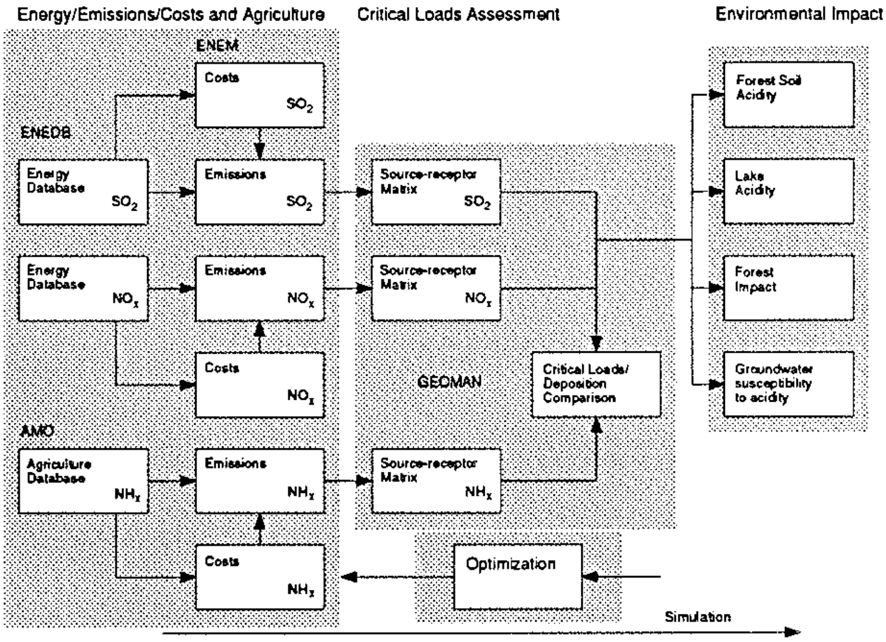

Figure 2.1. A schematic presentation of the structure of RAINS (version 6.0).

Three pollutants, sulphur dioxide, SO_2, nitrogen oxides, NO_x, and ammonia, NH_3, are described in the model. It should be mentioned that RAINS can be used only for analysing the impact of a single pollutant on the system at one time. Combined effects can be examined directly only within the Critical Loads Assessment Module.

Spatially, RAINS covers the whole of Europe (including the republics of the European part of the former USSR) in grid squares[1] with a resolution of 150 km x 150 km for emissions and atmospheric processes, and 0.5° latitude x 1.0° longitude for the environmental impact compartment (compartments and modules

1. The grid has been defined by the EMEP and is used in other models as well.

are terms used interchangeably about smaller or larger parts of a model that can work almost independently from other parts of the model. Submodels are used in the same sense. The difference is that a submodel can be even smaller than a module, and can be a part of a module).

The temporal long-term perspective is the period 1960 to 2000 (2040 for the soil impact submodel) where information can be obtained at 5 year intervals. The period 1985 to 2000/2040 represents perspectives on future developments.

RAINS can be operated in two modes: either by scenario analysis where impacts of energy consumption and emissions on the environment are analysed (follow the arrows in Figure 2.1 pointing right), or by optimisation analysis where overall European minimal costs are allocated, as for example an environmentally specified target (follow arrows in Figure 2.1 pointing left).

Under the operation of RAINS, the user is guided through the different submodels via a series of menu-driven options. On every menu a number of choices exist for displaying data/results, or initiating special calculations. Furthermore, the user can choose the previous menu (or exit the submodel completely), and then go backwards in the model structure. This is accompanied by a help facility which provides the user with information on the various options on the menu that can be read on the screen.

The required hardware for implementing and running the model is an IBM XT or AT 386/486 compatible PC. It is recommended that it be used with a coprocessor. The full program needs 8 MB disk space, and a core memory of 640 KB. Extended memory is recommended with the Deposition and Critical Loads Assessment submodel. The model has been developed on the code language FORTRAN and C.

Results of the calculations can be viewed on the monitor (EGA or VGA), saved on a file for later use, or printed out. Colours are utilized on menus and on resulting tables and graphs to improve the clarity of the results. The same set of colours are used on every output monitor thus securing consistency. Response time is usually a few minutes for calculations depending on the hardware equipment used and the specified task to be solved. Running the model through from top to bottom takes about 10 to 15 real time minutes.

RAINS consists of several different model types. *The Energy/Emission/Costs and Agricultural Module* is basically a database with options for simple calculations. *The Critical Loads Assessment Module* consists of various parts; a source-receptor matrix; a Geographical Information System (GIS, called GEOMAN) allowing for graphical display of European deposition patterns; and finally GEOMAN provides the facility for comparing estimated depositions with critical loads (Annex 1 gives a more detailed description of the acidification problem and related terms). *The Environmental Impact Module* represents more conventionally known simulation submodels describing the effects of deposition levels on natural chemical processes. Finally, *the Optimization Module* consists of an LP-solver (Linear Programming solver) that links deposition targets to energy use and economic abatement costs.

Basically, the submodels and compartments are linked so the output from one module or submodel is used as an input to another. However, the input to some models must be modified to fit into the model structure. This will be elaborated on further in the following subsections where the compartments are presented in more detail. The presentation refers to submodels describing sulphur as pollutant. Submodels referring to the other pollutants are not significantly different and it would be too extensive to go into details of this kind. It is the main aim of the description to present an overview of the RAINS model. Details can best be learned by actually operating the model.

2.1.1 Energy, Emissions, and Costs

One fundamental part of RAINS is the Energy/Emissions/Costs and Agriculture Module (referred to as the Energy/Emission/Costs Module). The compartment consists of three submodels that can be viewed in Figure 2.2 in terms of special characteristics.

Special features of the submodels are that all statistics and projections are combined in a common database format aggregated into country, year, economic and energy consuming sectors and fuel types used. The aggregation was made according to UN-ECE and OECD databases from which most data have been derived.

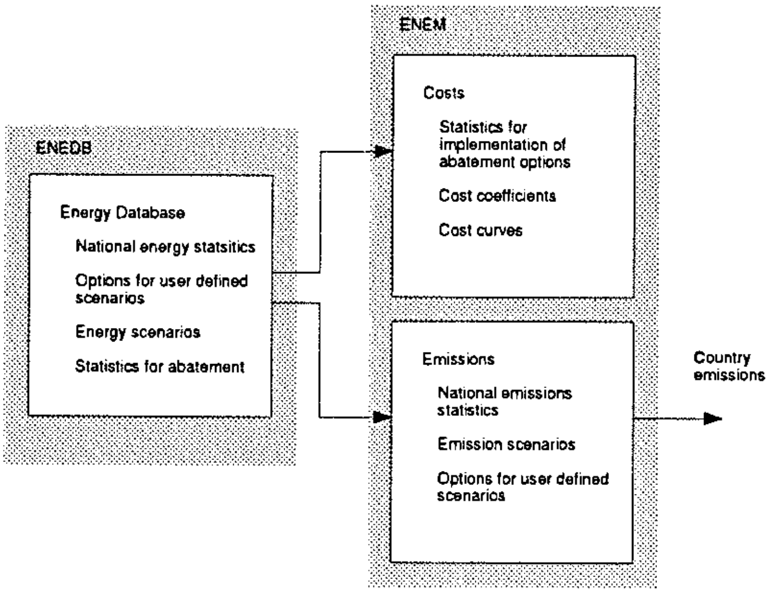

Figure 2.2. The submodels of the Energy/Emissions/Costs Module and their characteristics. The figure is related to the sulphur part.

The Energy Database, ENEDB is aggregated into 6 economic sectors, and 12 fuel, and energy-using sectors. Table 2.1 lists the sectors and fuel types along with their abbreviations that are used in the model as well as in this report.

Table 2.1. Sectors, fuel types and abbreviations used in ENEDB.

Economic Sectors	Fuel and Energy Consumption Sectors	
Energy Conversion, CON	Brown Coal, BC	Light Fraction, LF
Power Plants, PP	Hard Coal, HC	Gas, GAS
Domestic Sector, DOM	Derived Coal, DC	Nuclear Power, NUC
Transportation, TRA	Other Solids, OS	Hydro Power, HYD
Non-Energetic Use, OTH	Heavy Fuel Oil, HF	Electricity, ELE
Industrial Sector, IND	Middle Destilates, MD	District Heat, DH

Several energy scenarios have been created by the model developers and are built into the submodel. Some of the most important are:

- *The Official Energy Pathway (OEP)* which show national official projections (from 1992) for energy consumption as has been reported from member states in the Economic Commission for Europe (ECE).
- *The Eastern Europe Efficiency Scenario (EEE)* reflects assumptions which take into consideration the enhanced improvement of the energy-producing sector in the former Eastern European countries. It is assumed that efficiencies in the East correspond to those in the West in the year 2000. The basis scenario for the development was the Official Energy Pathway. *This* scenario is described in more detail in Amann *et al.*, 1992.
- *The Maximum Technically Feasible Reduction Scenario* shows projections of energy consumption after implementing the various abatement options included in RAINS. Again the Official Energy Pathway was used as the base scenario.

All scenarios may be the basis for user-defined scenarios in which the user can express individual, subjective viewpoints for the future development of energy consumption patterns.

Finally, within ENEDB options are also outlined for abatement control, i.e., fundamentally add-on technologies or fuel switching to less polluting fuel types. The options and combinations with sectoral aggregation can be seen in Table 2.2. The user can in this way create control scenarios which impact on the ecosystem can be analysed using other submodels.

Table 2.2. Pollution options for various economic sectors and fuels (source: Alcamo et al., 1990).

Sector	Fuel	Low Sulphur	Combustion Modification		Flue Gas Desulph.		Regeneration Process
			Retro	New	Retro	New	
Conversion	Hard Coal				X		
	Heavy Fuel Oil				X		X
Power Plants	Brown Coal		X	X	X	X	
	Hard Coal	X	X	X	X	X	
	Heavy Fuel Oil	X			X	X	
Domestic	Hard Coal	X					
	Coke Briquettes	X					
	Gasoil	X					
	Heavy Fuel Oil	X					
Transportation	Gasoil	X					
Industry	Hard Coal	X	X		X		X
	Coke				X		X
	Gasoil	X					
	Heavy Fuel Oil	X			X		X

The Costs Submodel is an important part of the compartment. Here cost coefficients, i.e., DEM (German Marks) per unit of sulphur removed or DEM per use of energy are estimated from technology and country-specific parameters and data. Parameters considered in the calculations are shown in Table 2.3.

Table 2.3. Technology and country-specific parameters and abbreviations used for estimating cost coefficients (source Alcamo et al., 1990).

Technology-specific parameters	**Country-specific parameters**
Investment costs, I	Sulphur content, sc
Coefficients for the Investment function, c_i^f, c_i^v	Heat value, hv
Technology lifetime, lt	Sulphur retained in ash, sr
Sulphur removal efficiency, x	Average boiler size, bs
Flue gas volume, v	Capacity utilisation, pf
Maintenance costs, f_i	Real interest rate, q
Specific demand for energy λ^e, labor λ^l sorbents λ^s and waste disposal λ^d	Prices for electricity c^e, labor c^l sorbents c^s and waste disposal c^d

Equations (2.1) and (2.2) are used for deriving the cost coefficients for abatement options which require additional investments at a plant site as a direct result of the pollution control. The costs of other abatement options are already converted to unit costs in the database and need no further conversion. These have been reported and published internationally by scientists and official sources.

Abatement costs per use of energy *unit: DEM/PJ*

$$c_{PJ} = \frac{I_{an} + OM_{fix}}{pf} + OM_{var} \tag{2.1}$$

Abatement costs per kt removed sulphur *unit: DEM/kt SO_2 removed*

$$c_{SO_2} = \frac{c_{PJ}}{\frac{sc}{hv}(1-sr)x} \tag{2.2}$$

where the investment costs are determined by

$$I = (ci^f + \frac{ci^v}{bs})\ \frac{v}{bs} \tag{2.3}$$

and used to determine the annual investment costs

$$I_{an} = I\ \frac{q^{lt}(q-1)}{q^{lt}-1} \tag{2.4}$$

The fixed operating and maintenance costs are given by

$$OM_{fix} = I\, f_i \tag{2.5}$$

and the variable operating and maintenance costs are determined by

$$OM_{var} = \lambda^l c^{\,l} + \lambda^e c^{\,e} + \frac{sc}{hv}\,(1-sr)\; x\; (\lambda^s c^{\,s} + \lambda^d c^{\,d}) \tag{2.6}$$

Cost coefficients (c_{PJ} and c_{SO2}) are the basis for estimating the national cost curves. These cost curves represent the lowest costs to achieve different emission reductions. It is assumed that each country can reduce its emission up to a certain percentage of the uncontrolled emission rates at stepwise increasing costs. Two curves are estimated (relating to a specific energy scenario, year and nation) using a specially developed algorithm: The marginal cost curve expresses the costs in DEM/t SO_2 removed for the different emission reduction strategies, and the total national cost curve gives the annual costs in DEM/year.

The curves are constructed using the total pollution costs that are estimated as follows:

$$C_{tot} = C^{\,d} + C^{\,P} \tag{2.7}$$

where the control cost for process emission removal C^P is given by

$$C^{\,P} = S^{P*}\, x_P\, C_P \tag{2.8}$$

and the direct abatement cost C_i^d is determined by

$$C_i^{\,d} = \sum_j \sum_k \sum_l E_{i,j,k,l}\; c_{PJ,i,j,k,l} \tag{2.9}$$

S^P represents the sulphur emission from an industrial (non-combustion) process. x_P is the efficiency of process emission removal. C_P is the unit cost for sulphur emission removal. E determines the energy consumption in the i'th country, using the j'th fuel type, the l'th abatement technology, and the k'th economic sector.

Further details can be found in Amann (1990).

The Emission Submodel is the second part of the Emission and Cost complex, ENEM. The submodel includes statistics and facilities for estimating national emissions. National statistics are expressed in so-called emission scenarios that differ from the energy scenario in representing only future expectations of national emissions without specific considerations on how they may be achieved in the energy consumption sectors.

The total national sulphur emissions is estimated as:

$$S_i = \sum_j \sum_k S_{i,j,k} + S_i^{\,P} \tag{2.10}$$

and the total sectoral emission for a given fuel is:

$$S_{i,j,k} = \sum_{l} E_{i,j,k,l} \frac{sc_{i,j,k}}{hv_{i,j}} (1 - sr_{j,k})(1 - x_{i,k,l}) \tag{2.11}$$

The suffixes are as explained above.

One important scenario already implemented in RAINS is the *Current Reduction Plan (CRP) scenario* where the individual countries have expressed their official political expectations for future emission levels. This scenario may be the basis for user-defined emission scenarios where, for example, the user can analyse the effect of reducing current emissions by a certain percentage. Also the earlier-mentioned energy scenarios are represented as emission scenarios. It should be pointed out that emission scenarios based on user definitions in the Emissions Submodel do not have a corresponding energy scenario in the Energy Submodel.

2.1.2 Critical Loads Assessment Module

The country emissions from the Energy/Emissions/Costs and Agriculture compartment is used directly as input to the Critical Loads Assessment Module. The structure of this compartment differs significantly from similar acidification/air pollution models[2] and may be one reason for the relatively widespread recognition of RAINS. The submodels and special characteristics of the compartment are schematically presented in Figure 2.3.

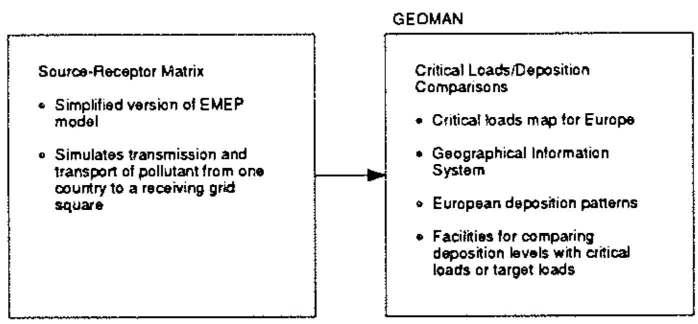

Figure 2.3. Submodels of the Critical Loads Assessment Module and their characteristics.

The Source-receptor Matrix links the anthropogenic emission sources to the acidic deposition. The submodel basically "translates" country emissions into depositions in receptor grid squares by assuming linear relations between the long-range transport distances of country emissions and deposition values. Elements in the matrix express the deposition per unit area per unit time for one unit emission transported from one country to a receiving grid square or country.

The model uses source-receptor matrices made under EMEP model runs. The model used in EMEP is highly complex and simulates the effects of winds, precipitation, and other chemical and meteorological variables on acid deposition and air concentration. The model has been based on observations in the European countries and has been extensively validated. The use of the EMEP source-receptor matrix in RAINS make it possible to perform such calculations on a PC

2. See section 2.3 later this chapter for details about familiar models.

in a reasonable time.

In earlier versions of RAINS, four source-receptor matrices have been estimated and implemented, each representing a different meteorological year. The user could select the year to be the basis of the results. A matrix representing average values of the four years is often utilised as a "guess" on a situation not linked to a particular year and to account for variations from one year to another.

Output from the model calculations can be seen in a table showing the amounts of sulphur which are emitted from one country and deposited in another. This information is dumped, on request, into a file that can be printed or can be used as input to the Critical Loads and Deposition Comparisons Submodel.

GEOMAN is a Geographical Information System (GIS) and constitutes the framework for the ***Critical Loads and Deposition Comparisons Submodel.*** GEOMAN is a data storage and display system for environmental information. GEOMAN has also been developed at IIASA. The linking to the RAINS model makes it possible to view graphically the European deposition patterns resulting from various scenarios. The deposition patterns are displayed as gridded maps showing either a numerical value or displayed as a colour representing a range. GEOMAN replaces most functions of the Deposition Module of earlier versions of RAINS, and increases options for analysis of the deposition patterns.

The submodel contains the database on critical loads (see Annex 1 for comments on critical loads and acidification) compiled by the Coordination Center of Effects, RIVM, Bilthoven, the Netherlands. This database contains for each EMEP grid cell a cumulative frequency distribution of the Critical Loads of sulphur and of total acidity. In this way the results of an energy strategy can be assessed by comparing the deposition values to the officially accepted levels which form the goals for emission reductions in Europe.

The Critical Loads frequency distributions are expressed in terms of percentiles. The user can then select the percentile to be used as a basis for the comparisons. The most commonly used percentiles are 1 and 5.

There exists four possibilities for assessing the results of the deposition pattern. Primarily, the deposition patterns can be viewed. One option shows for each grid the percentage of the ecosystem where the critical load value has been exceeded. Another option shows the exceedance (in absolute amounts) of the chosen critical loads percentile. The last option shows exceedance of target load values of the deposition levels; these are values set by the individual countries themselves and collected by IIASA.

All results can be saved on files and loaded again for later use. The grid data can be combined arithmetically; their square roots or their logarithm can then be calculated. Weighting factors can be specified setting the personal preferences on the "score" that the various results should have on the calculations.

Subjective viewpoints on data sets can be loaded into GEOMAN. These have to be in a dBASE file and aggregated into the EMEP grid net sizes. All maps can be printed out on a common Postscript printer.

The submodel differs from other RAINS submodels in structure and ways of operationalising it. It is based on a framework similar to the software package Windows where several screens can be seen at the same time. This enables the user to keep the overview of the structure of the submodel and selected options.

Calculations taken in real time only approximate one minute on a 486 PC. Help facilities are available using the submodel. However, this option is not yet fully elaborated since not all comments give a full description of the option or files to be selected. These things will undoubtly be improved in time.

To the author's knowledge the development of this submodel has been greatly emphasised by the work in the ECE-Task Force Groups and shall therefore be regarded as an attempt to make RAINS more policy oriented. The Critical Loads and Deposition Comparisons Submodel plays a central role in the use of RAINS as a policy tool since the Critical Loads maps are used as goals for setting the European emission levels (see section 2.4 of this chapter for more details on the practical usage of RAINS).

Results of the Critical Loads Assessment Module form the input to the Environmental Impact Module and the Optimization Module.

2.1.3 The Ecological Impact Module

The Ecological Impact Module is divided into four submodels, namely, the Soil Acidification Submodel, the Lake Acidification Submodel, the Forest Impact Submodel, and Submodel for Groundwater Susceptibility to Acidity. These are the parts of the ecosystem for which it is likely that acid deposition has a certain negative effect on the stability, growth, and state. The last-mentioned submodel is not yet operational and will receive no further comment.

Some general points can be stated about the submodels. Input to the submodels is the estimated pollutant concentration (sulphur or nitrogen deposition) resulting from calculations of the Critical Loads Assessment Module. They all simulate relatively complicated chemical reactions taking place in nature.

It is beyond the scope of this presentation to go into a detailed description of the submodels since this would require some commentary and definitions of chemical processes. The submodels are commented on only briefly, focusing on the results of using the submodels.

The Soil Acidification Submodel simulates the year-to-year development of forest soil acidification in an idealised 50-cm deep soil layer. The soil acidification submodel constitutes an important link between air pollution and damage to the terrestrial and aquatic environment. The ability of the soil to buffer acid deposition is a key factor in regulating the long-term surface environment.

Preprocessing of the input to the Soil Acidification Submodel is required in the sense that the deposition resulting from the sulphur and nitrogen emissions associated with the scenario needs to be simulated into pH values. This is done by selecting this specific option in the submodel.

The outputs from model calculations are presented in terms of various maps showing either the state of soil acidification (in pH values) in selected countries, or the time evolution of forest area below certain pH values. Bar diagrams show the ranges of pH values in a country, an option that is also possible to enable comparsons to be made with other scenario values. Furthermore, the ranges of pH values in a region aggregated into grid squares can be seen.

Again graphic presentation of the results play a central role. However, operating the submodel demands that we have a relatively deep knowledge of the chemical definitions and mechanisms for acidification, since some constant values must be set by the user.

The Lake Acidification Submodel aims at describing processes of lake chemistry in freshwater lakes. Again, input to the submodel must be prepossessed into pH values or alkalinity values.

There are two main options for simulating lake catchment processes in the Fennoscandinavian countries Norway, Sweden, and Finland. First the mean annual lake pH for one energy scenario and year may be simulated. A table with three columns is produced for each country; the first and last columns designate the percentage of lakes within a district with pH values less than the lower and greater than the higher pH criteria value, respectively. The middle columns include those lakes whose pH values are between the lower and upper threshold values. A graphical display of the distributions can be shown. The calculations performed with one energy scenario may be compared with another scenario or year. Both scenario values may be displayed on the maps. As another option, annual lake alkalinity for one or two selected energy scenarios and years may be simulated.

The Direct Forest Impact Submodel attempts at simulating important causes of forest dieback in Europe. The submodel is based on empirical data of forest dieback from the former Czeckoslovakia. The submodel has been formulated as a statistical/empirical model of effective SO_2 dose. The input to this submodel is the annual average air concentration of SO_2 which is taken from the Critical Loads Assessment Module. The principal output is accumulated doses of SO_2 to trees which is a simple computation of concentration times exposure time. Dose accumulates if a threshold SO_2 concentration is exceeded, and damage to trees is assumed to occur if the accumulated dose exceeds a threshold level. Regional differences in the tolerance of trees to climate conditions are accounted for by making the threshold dose level a function of a variable representing annual values of the length and warmth of the growing season.

Output of the model can again be displayed on maps showing the distribution in different classes of forest representing the level of risk of damage in this grid square as well as the effective temperature sum in grid squares or percentage of forest area in the region.

2.1.4 The Optimization Module

With the ***Optimization Module*** (OPT) alternative emission abatement strategies can be formulated and their optimal solutions, in terms of the European allocation of costs and corresponding emissions, can be found and compared.

The Optimization Module is operated by going through steps in a menu form. Firstly, the scenario and year (and therefore the cost curves to be used) are specified. Here it is important to note that a special algorithm groups the cost estimates of the national cost curves into approximately 8 fractions that represent the step-wise values of the cost curves in the optimisation.

Afterwards, the problem to be solved shall be formulated, this is done in the form of a Linear Programming (LP) model which is either receptor or source oriented. *Receptor-oriented objective functions* are based on environmental and/or policy indicators, as for example minimisation of total European costs, or minimisation of European emission removal. The national cost curves impose limits on the amounts of emission/costs that can be removed/invested. *Source-oriented goals* ignore environmental indicators. A typical objective function would either minimise the total European costs with a total emission requirement, or maximise the total European emission removal with a budget constraint. The last mentioned objective function uses a simple sorting algorithm while the first-mentioned objective function uses a linear programming algorithm.

For the most commonly used receptor-oriented problem, a set of constraints must also be specified. These may be either environmental indicators, relating to deposition or pollutant concentration targets at selected receptors (which may be grid squares of countries), or policy indicators relating to minimum and maximum emission abatement removal. A large number of indicators increase the complexity of the LP problem and correspondingly the time to solve the problem on a PC.

Typically, the optimisation problem can be formulated as

$$\min\Big[\sum_i cost_i(emis_i)\,\Big|\,\sum_i a_{ik}emis_i \le d_k,\ k=1,2,\ldots,K \qquad \underline{emis_i} \le emis_i \le \overline{emis_i},\ i=1,2,\ldots,I\Big] \tag{2.12}$$

where

a_{ik} is the transport coefficient (from the source-receptor matrix) giving the amount of sulphur deposited at receptor k due to a unit of emissions from source i (in a certain time interval), i = 1,2,...,I; k = 1,2,...,K.

$emis_i$ is the emission from source i.

$\overline{emis_i}$ is the maximum (i.e., unabated) emission from source i.

$\underline{emis_i}$ is the minimum emission (corresponding to maximum feasible emission reduction) from source i.

$cost_i(emis_i)$ is abatement cost yielding one unit of emission ($emis_i$) from source i.

d_k is the deposition target at receptor k.

In order to simplify the LP problem and check the feasibility of the solution, four so-called filters have been included in the Optimization Module. These filters remove receptor locations and corresponding targets that do not affect the solution of the problem. The first filter physically removes receptors that may be specified twice. The second filter removes receptors which always meet the specified deposition/concentration target using the unabated emissions. The third filter removes receptors which are always dominated by other receptors. Finally, filter four checks the feasibility of the constraints to see if deposition/concentration targets can be obtained under circumstances of full abatement (corresponding to minimum possible emissions). The filters may be used individually, sequentially, or not at all. In the case where a feasible solution exists, the optimisation may then be performed.

The output from the optimisation calculations can be obtained in three ways: summary which gives the estimated emissions, country costs, and total European emissions and costs, table showing the removal costs and percentages from a base year attributable to each country, and the average removal costs per ton pollutant for each country, and finally, the output in the form of receptor depositions at each receptor can be seen for unabated, fully abated and optimal emissions.

2.2 Use of RAINS

The usage of RAINS extends widely from scientific presentation and reporting of the modules and submodels, scientifically related findings of analyses, findings used as policy-raising issues, and incorporation with other models in order to show detailed or new aspects of science or political dimensions. Additionally, RAINS has been documented through a number of studies concerned with various aspects of uncertainty or sensitivity associated with the components of the model. These will be commented on in Chapter 4.

In order to give an idea of the possibilities in using Integrated Environmental Models, the way RAINS has been used and is presently used in different studies is commented on below.

2.2.1 Scientific and Technical Usage

The RAINS model has been presented to a broad public ever since it was firstly developed in the middle of the 80s. That it is aimed at a broad public can be seen by the various papers presenting the model. In Alcamo *et al.* (1987) RAINS was officially presented at the first time in a paper going through the whole model in its components and use. This publication was rewritten in Alcamo *et al.* (1991) that shall be seen as a small report stating what RAINS is and which findings have been reported upon by use of the model. Many publications exist that in some way describe the data, a single submodel, or function that can be used in the model. Some of the most important publications presents the data in the Energy/Emission/Cost and Agriculture Module of which can be mentioned Amann and Kornai (1987) presenting the data and calculations for the cost functions; Amann (1989) presenting the nitrogen emission estimates and cost coefficients for the nitrogen part of the model; Klaassen (1991) where the agricultural part of the model was presented; and finally Amann and Sørensen (1991) where the status for 1991 of the energy and sulphur emission database was given as a basis for the ECE Task Force members to respond to the values in order to improve the estimates.

The optimisation module is presented mostly as a part of the description of the cost curves and in connection with more practical usage of the model. However there exist a few publications referring to the optimisation module itself of which can be mentioned Lübkert *et al.* (1990).

Naturally, other parts of the model have been presented and documented. The most extensive documentation can be found in Kämäri (1990), where the impact submodels are presented.

Finally, the comprehensive book by Alcamo *et al.* (1990) must be mentioned, since in this book all modules and submodels are presented in terms of assumptions, scope, limitations for use, possible ways of using the modules and submodels, and finally by providing the reader with an overall list of publications where additional information can be found. It shall be mentioned, however, that the book refers to the RAINS version 5.1 which has not incorporated the Critical Loads Assessment facilities.

To the author's knowledge there do not yet exist a documentation of the version 6.0 reported on in this chapter.

Also not many other models appear to exist that are so well documented in publications that are accessible for the public.

2.2.2 Integration With Other Models

Due to the approach with which RAINS was developed there are naturally limitations on which problems can be solved using the model. A few attempts have, therefore, been made on integrating the RAINS model into other model frameworks. There do not exist many official papers on these aspects. However, one can mention Stam *et al.* (1992) where the RAINS model, or more specifically parts of RAINS have been tried connected to a so-called Decision Support System. The aim of this study was to gain insight into the dynamics of the acidification problem seen as a system consistent of costs and benefits to tradeoff within the different European countries. Data for the RAINS Emission and Cost submodels were used as input to the Decision Support System that was built for providing insight into multiple criteria analyses. The paper gives a detailed but technical description of the system, and can be perceived only as an academic exercise.

2.2.3 Policy Analysis and Strategy Development

As a natural consequence of developing RAINS with the purpose of giving input to the policy discussions, many publications exist on exactly these issues. Instead of just listing most studies, the author has selected only a few that are typical examples of the use of RAINS for providing input to the policy-making discussions.

In Amann *et al.* (1991) different scenario runs have been performed and reported on as input to the UN/ECE Workshop held at IIASA in June 1991. This workshop was intended as prenegotiations on the European sulphur protocol that was to be established during 1993/1994. It mainly presented different ways of creating various strategies to be solved by optimisations. The results of these optimisations are then displayed as figures and deposition patterns in Europe. The different scenarios are discussed in terms of economic and environmental benefits to give the participants of the workshop an idea of what RAINS is and can do but also of the scope of the findings that can be found using the model. The purpose of the presentation was to invite the participants to create their own ideas to be investigated with RAINS. It shall be mentioned that the decision makers present at the meeting did not operate the model themselves. Various ideas/analyses were presented by the model developers in parallel with the discussions.

Amann *et al.* (1992) constitutes a more broadly aspected paper that aims at directing attention at simpler solutions for reducing acidification levels in Europe. This paper presents one scenario in which the former Eastern European countries are assumed to have energy policies in the year 2000 that match those of Western Europe in 1985. This basically means that each country's energy efficiency is changed in accordance with those of the Western Europe and that the infrastructures of the Eastern European countries will change to make this possible. The scenario is presented and compared with existing scenarios, and different model runs are performed and discussed in terms of economic and environmental benefits of such changes in both the East and West. At the outset, such studies can seem of minor importance since they are a sort of supposition that assumes almost the impossible. On the other hand they help raise questions and possible ways of answering them. The studies shall therefore not necessarily be taken as ultimate studies but more as "appetizers" to be responded upon by the decision makers.

The most recent usage of RAINS is perhaps in the reports for the preparation of the European Community's Fifth Action Programme on the Environment (see, for example, Hettelingh (1992), and RIVM (1992)). The Community aims at making an action programme for all the European countries. The programme shall approach the major environmental issues of the Community under the concept of sustainable development[3]. It is an overall study that directs environmental problems at global, regional, European and local scale. In its approach it is similar to the Dutch National Environmental Policy Plan (see NEPP, 1989, and Sørensen, 1993b) that has been the inspiration for the Community's plan. RAINS is used to assess the impact of acidifying emissions of various assumptions of the development of all European countries.

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3. Sustainable development shall be understood in broad terms as defined in the UN (1987) report.

2.3 Related Integrated Models

The RAINS model is but one example of Integrated Environmental Models addressing the European acidification problem. There are many similar models around in the different European countries and institutions. Four of the most documented and discussed models are presented shortly in this section. The models are named ACIDRAIN, ASAM, BICRAM, and CASM. They are similar in their approach for describing cause-effect relationships of the acidification problem. However, the model structure, calculations, and way of presenting the results as well as how they handle uncertainties differ. The description will be followed by a comparison of these models with that of RAINS.

It should be noted that other models also exists. Two that are related to acidification problems in North America are the ADAM model (see, for example, Alcamo *et al.*, 1990), and the ADEPT model (see for example Rubin, 1989). They are similar in structure to RAINS and ACIDRAIN, respectively. The models are commercially available and used; in at least two US states the recommendations of the ADEPT model have been followed. The author sees these two American models as inspiration for the European models.

The following presentation is based on Dixon (1992), Rubin (1989), Alcamo *et al.* (1990), and ApSimon *et al.* (1991), since the models have not been in the hands of the author.

2.3.1 The ACIDRAIN Model

The ACIDRAIN model was (and is currently) developed at Cambridge Decision Analyses, Cambridge, United Kingdom. Initiation of the development was requested and economically financed by the UK Department of the Environment.

The model is built on a decision analysis[4] framework, that allows for interactive use and analysis. It is designed to be used by policy analysts themselves.

Fundamentally, the selection of model components, i.e., structure, functional forms, parameters, variables, etc., must be made by the user. The model incorporates alternative functional forms built in, and data that represent key components of the integrated analysis (source-receptor relationships and dose-response functions for evaluating damages from acid deposition).

The model is relatively simple, requires a minimum of data, and has a limited spatial and aggregational coverage. It covers 6 spatial regions in the UK and 3 in Western Europe on both the source and receptor side. The time schedule is the period 1980 to 1995.

Main model components are: emissions and UK control costs of abatement; atmospheric deposition; damage functions for lakes, forests, crops, buildings, monuments, human health, and unit damage prices. In order to compare emission reduction costs and reduced environmental damage, values may be selected and attributed to the latter. Temporally, effects are calculated as a function of the current pollution level ignoring possible cumulative effects.

Technically, the model requires an IBM XT/AT with colour monitor. The programme size is of 500 KB and it requires 720 KB space. Lattice C has been used as programming language. The program is run by simple menu selection. It is possible to run 100 strategies in 1 hour. Results of the model runs are presented in four different colour monitor formats.

4. See Howard (1983) for comments on the decision analysis approach.

Presentation of uncertainty. ACIDRAIN has facilities for directly expressing uncertain variables in the model where continuous probability based on Latin Hypercube sampling[5] can be assigned to the variable values. All variables in the model (up to 200) can be represented by probability distributions. The uncertainty is described as triangular probability distributions whose minimum, maximum, and mode values must be defined by the user. It is assumed that all distributions are independent. There are three options for running the model uncertainties: modal run (1 model run), scoping (10 runs), and full simulation (150 runs). Outputs of the analysis are presented by means of histograms and bar charts showing the correlation between input and output variables.

The uncertainty that exists as a result of the choice of alternative structural forms of the relations in the model cannot be explicitly expressed.

2.3.2 The ASAM Model

The *A*batement *S*trategies *A*ssessment *M*odel, ASAM, is being developed at Imperial College, London, United Kingdom. It is a direct outcome of the Bergen Conference on Sustainable Development held in May 1991 (ApSimon *et al.*, 1991). At this conference a need was expressed for developing cost-effective abatement strategies for sulphur and nitrogen reduction. ASAM is developed in this context as a computer tool for guiding policy makers through the investigation of the effectiveness of potential abatement strategies in Europe.

The model is very similar to the RAINS model in structure and scope. ASAM has combined four modules describing sources and their emissions, source-receptor relationships (atmospheric transport and deposition), target loads for deposition, and options to abate sources of different types and the allocated costs for their implementation. The model utilises the estimated emissions, and source-receptor relations as given by the EMEP model. The spatial resolution of ASAM is a result hereof the whole of Europe divided into the EMEP grid squares.

In the current version of ASAM, emissions of sulphur dioxide can be obtained for each of the grid squares based on the different sources (e.g. plants) allocated hereto. This gives in principle the possibility to explicitly treat major point sources and different types of ecosystems within the grid structure.

The data for finding the cost of various abatement options as estimated in the RAINS model, is utilised also in the ASAM model. However, the construction of the natural cost curves is based on a simulated annealing algorithm (see, for example, Jørgensen *et al.*, 1991) (and not an LP-optimisation as in RAINS).

The model has no facilities for handling uncertainty explicitly. This can be done mainly through a scenario analysis.

2.3.3 The BICRAM Model

The *B*eijer *I*nstitute *C*ontrol *R*esources *A*ssessment and *M*anagement (BICRAM) model is developed at the Beijer Institute, Stockholm, Sweden and University of York, York, United Kingdom.

In complexity and structure this model is also very similar to the RAINS model. The BICRAM model is built with the purpose of identifying efficient cost-effective strategies for achieving deposition targets. Spatially, the model covers the European countries in the EMEP grid squares. The timely prespective is the

5. See Sørensen (1993a) for comments about Latin Hypercube sampling.

period from 1960 to 2040 where information can be obtained annually or seasonally. Main components of the model are: emissions, control costs, atmospheric deposition, soil pH, lake acidicity, groundwater sensitivity, and forest impact.

Technical uncertainty is handled through scenario analysis.

2.3.4 The CASM Model

The *C*o-ordinated *A*batement *S*trategies *M*odel, CASM, is developed at the Stockholm Environment Institute, Stockholm, Sweden. To my knowledge the development of this model is based on the BICRAM model.

The CASM model is used to investigate a number of different abatement strategies. It is sharply focused on comparing deposition levels with target maps. The Stockholm Environment Institute has developed an ecosystem sensitivity map, which is included into the CASM model. This map was the first critical loads map developed (see Annex 1).

The main components of the model are: sulphur emissions, total national costs of abatement, deposition across EMEP grid squares, and exceedance of the ecosystem sensitivity map values. CASM has furthermore the facility to investigate optimisation to achieve damage minimisation under the assumption that damage to ecosystems is proportional to the sensitivity level attributed to the ecosystem. In abating the emissions, unit depositions are weighted according to the sensitivity of the area on which deposition would occur. As another facility the user can set target loads assigned to smaller subsquares when running the optimisation routine in order to minimise deposition exceedance in ecosystem damage.

Technical uncertainty is handled through scenario analysis.

2.3.5 Comparing the Models

The models, ACIDRAIN, ASAM, BICRAM, CASM, and RAINS address the same problem of European acidification, and all are they developed with the aim of supporting policy analyses and decisions on this issue. As a result hereof, they have a size and man-machine interface so they can be implemented on 386 or 486 IBM compatible PCs.

Common features are that the models are developed from relatively simplistic principles, meaning that the modules and submodels constituting the models perhaps do not use the equations describing all complexities of the smaller system to be described. Instead, results and data from more-detailed models (used for more sophisticated scientific purposes) are utilised in simple mathematical equations and relations.

The ASAM, BICRAM, CASM, and RAINS models are similar in this model structures and data used. All of these models have approximately the same number of components (modules) that describe the causes and effects of air pollution as well as the costs its abatement. They are based on a systems analysis approach and use simulation and optimisation as technical problem-solving techniques.

The ACIDRAIN model has been developed from a completely different approach and focus (more detail is put into the description of the UK than the rest of Europe). But this model focuses also on scenario experimentation through simulation.

Also the models are based on scenario runs for exploring aspects of the problem. In the models where optimisations can be performed (RAINS, ASAM, and CASM) this facility is considered of great importance in the analyses.

To a certain extent, the data input can be performed by the user him/her self. The level of interactiveness is highest in the ACIDRAIN model where nearly the entire model, in overall and more detailed structure, can be defined by the user. The interactive facilities are more constrained in the other models. Here this facility is limited to implementating subjective values for scenario generation and runs, and specifications of goals and constraints for optimisation runs.

The ACIDRAIN model is special not only in its modelling approach but also in the way it handles uncertainties of the variables and parameters in the model. The uncertainties are handled in two ways, namely through probabilistic description and scenario analysis. The last-mentioned approach is also utilized in the other models. The specific handling and focus on uncertainty in ACIDRAIN must be seen as a positive feature since the existence of uncertainty is recognised and expressed in quantitative terms enabling the user to relate to it and take it into consideration in the analysis. On the other hand, the probabilistic approach gives only a limited frame for uncertainty characterisation since uncertainties are present that are not easily characterised with probabilistic approaches (see Sørensen, 1993a,b).

The lack of a more methodological treatment of uncertainties in the Integrated Environmental Models must be said to be a major problem.

It is not possible to go into a detailed comparison of the models when they have not been in hand, and when the written documentation of the models is limited. However, from the literature and the international discussions in the Task Force Groups (where the author has been present on a few occasions) it can be concluded that

- a certain bias exists within the models. Almost all of them use data and results from the EMEP model. The RAINS model and the information, especially on abatement costs, is utilised also in the other models as well. Some work of the Task Force Groups is addressed to finding a consensus on various aspects and data utilised in the models. Naturally, this introduces a certain bias but is also a signal to the users of the scientific consensus that raises the level of credibility to the modelling.

- the models are difficult to compare in terms of results they are able to provide in spite of their obvious similarities. The "smaller" divergences of the model approach, solution techniques, and incorporated data make it impossible to comment specifically on why the results of the different models differ. In spite of this they are considered to provide results that in broad terms are comparable and can be used especially for comparative studies.

- facilities are lacking for treating of uncertainty in the models. They are described with only limited facilities for performing uncertainty analyses by direct use of the model. These aspects are addressed more in single studies where the results hereof are not given in the models but in publications and internal reports.

- the models are used mainly in analysis studies performed by the model developers themselves. There is clearly a lack of use of the models by decision makers/planners, and officials concerned with the regulation of the acidification problem. There can be many reasons for this but seen from the author's point of view this must be attributed to the confusion concerning the different models and difficulties in using them. There is a certain amount of competition among different institutions in their search for scientific recognition. This is especially expressed in terms of verbal presentations of the models in the same forums, and discussions on why the use of any one approach or data value is more justified than another. It is a sound discussion but simultaneously raises the level of confusion for the users and make it difficult for the users to choose the model that matches their specific needs.

The RAINS model must be assessed to be the one with most comprehensive work behind it. The databases and components are developed from internationally recognised sources, and it has been in the lead with documentations of the model, results of analyses studies, and in the readiness to change points in the model or expand it to meet the needs of the decision makers. It is also the model that is most utilised in the international negotiations on emission reductions.

2.4 Summary

The Regional Acidification INformation and Simulation model is presented in terms of concept, scope, and range. It was developed on a systems analysis approach and is currently used in ECE emission reduction negotiations. The Integrated Environmental Model consists of four large modules each divided into smaller submodels. Technically it is represented by various model types ranging from databases, simulation models, and an optimisation model to a Geographical Information System.

RAINS has been documented in several papers. Additionally, it has been utilised as input to discussions of acidification-related issues. It was lastly used in the European negotiations on sulphur emission reductions, and in the working papers for the European Community's Action Programme on the Environment.

However, other so-called Integrated Environmental Models are available which address the acidification problem. Four of these are mentioned: the ACIDRAIN model, ASAM model, BICRAM model, and CASM model. There are similarities and differences between the models. Comparing the RAINS model with them shows that RAINS is the one most well-documented and used, and has been employed more or less in the development of the other models.

3 Sensitivities of Costs in RAINS

The costs of different abatement options is of particular interest in the search for cost-effective emission reduction strategies. A need has been expressed for assessing the quality of cost calculations in RAINS in terms of sensitivities. This chapter will present an analysis on precisely this issue. The analysis was performed by the author at a stay at IIASA in 1991, and the test at that time was made using the RAINS version 5.1.

3.1 Idea and Basic Assumptions

As already outlined, the costs of abatement options are expressed and used in RAINS in three parts, namely, as cost coefficients, cost curves, and as a result of a performed optimisation. These estimates are presented in a highly different form: as estimates related to a country, energy sector, fuel type, energy scenario, and abatement option; as curves related to a country, energy scenario and year; and estimates related to the individual European countries, energy scenario and year. These are illustrated in Figure 3.1.

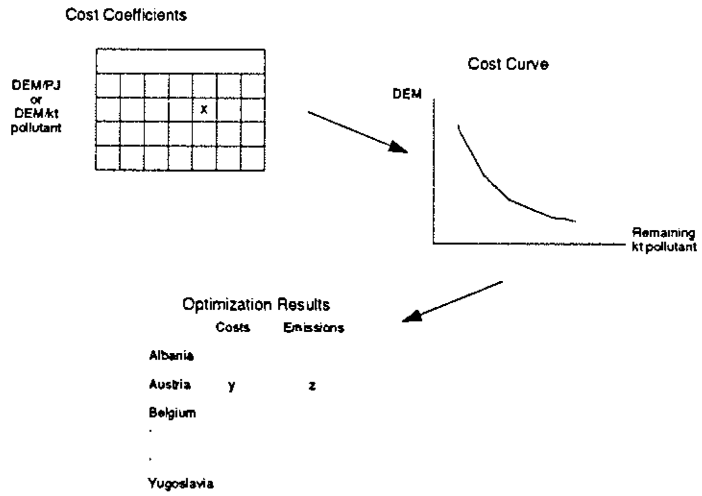

Figure 3.1. The various estimated costs in RAINS.

The cost coefficients are used to form the cost curve for a specific country. The cost curves are used in optimisation runs for which the results are presented as the European allocation of abatement costs to achieve the targets of the optimisation problem.

A sensitivity analysis studies the influence of variations in model parameters, initial conditions, etc., on model outputs. The present analysis concentrates on the influence on costs calculations of varying single parameters.

A large number of methods for performing sensitivity computations are known. A literature study shows that most tests which actually are seen to apply to models can be divided into two parts, namely, tests based on differential analysis, and those based on probability theory. Basically, the tests based on differential analyses seek a measure of the sensitivity of a single parameter or several parameters changed simultaneously. The methods can be found in different variations, and relevant references can be Dunker (1981), Behrens (1979), Tilden and Seinfeld (1982), Mahmond and Younis (1990), and Wong (1980). In most cases the sensitivity of parameters are analysed in order to identify the parameters leading to a desired model behaviour. The methods are based on complex mathematics that make specific assumptions about the structure of the model equations, and the knowledge about the parameters, and generally these methods are seen as applied to systems that are described in linear or nonlinear differential equations.

Examples of methods based on probability theory are the Fourier Amplitude Sensitivity Test (FAST) described in, for example, McRae *et al.* (1982). This method is based on probability theory where the output of the variables of a model are Fourier analysed. The Fourier coefficients represent an average of the output variables over the variations of all the parameters. Spear and Hornberger (1980) adopted a similar strategy in their Generalized Sensitivity Analysis. This test assumed *a priori* probability distributions of the parameters and determines through model runs the variations from the normal pattern of model behaviour. It can be discussed whether these tests shall be considered as sensitivity tests or uncertainty tests since they actually give the probability for a specific outcome of a model run.

As another part of the probabilistic methods, the stochastic programming (see for example Ellis *et al.*, 1986) can be mentioned, where variations in the objective function or criteria in the optimisation equations are expressed in probabilistic form.

Looking upon the nature of the calculations in the RAINS model it soon became clear that these methods had some disadvantages. The criteria for selecting the present analysis was that is had to be simple and easily understandable both in the approach and results of the test. It followed that the ideas of the test should be applicable to all three parts of the cost calculations. These criteria excluded most sensitivity analyses, since most of them have a limited applicability. Due to the differences in representing the estimated costs in RAINS, and the bias within these costs, it was decided to apply a form of conventional sensitivity analysis to the problem. Conventional sensitivity analyses (see, for example, Morgan and Henrion, 1990) are based on expressing a sensitivity measure of the variations of the parameters. The approach is in turn based on a Taylor series expansion of the sensitivities (see later in section 3.2). The modification requires that the present test be based more on trial-and-error exercises contrary to analytical expressions of the sensititivities. This was seen as a necessary step since the calculations of the RAINS model not can be viewed exclusively in terms of individual calculations. Within the model the calculations are exposed to measures and algorithms that cannot be seen directly as a part of the model calculations, but show up only after a closer view. One example is the algorithm which changes the original cost curves comprising about 20-30 single points into a stepwise linear cost function of about 8-10 single points which are utilised in the optimisation calculations. It must be remembered throughout that the calculations are a part of a larger model structure, and it is the viewpoint of the author that the single calculations cannot be seen in isolation as would be implied in the analytical expressions of sensitivities.

The present approach was based on the idea of following the effects of changing input value as it propagates through the costs calculations of the model. First, the influence of input parameter on cost coefficients changes was studied, secondly, the effects on cost curves were noted, and lastly those on optimisation calculations.

The fundamental purpose of the test was to determine the importance of input parameters on model results by changing the parameters and noting the magnitude of the changes on the results.

The basic assumptions behind the test are:

- The influence on cost coefficients, cost curves, and optimisation solutions due to changes in specific input parameter values has been analysed
- All results are based on calculations and data concerning sulphur pollution
- Input parameters included in the test were:
    - the investment function, I, indirectly by changing the boiler size, bs
    - the energy prices, c^e
    - the capacity utilisation of power plants, pf
    - the sulphur content of fuel, sc, for all fuel types and sectors
- Variations were made by a series of model runs for ±1 %, ±10 %, ±25%, ±50% and ±75 % changes of the original RAINS parameter value
- The changes were made by altering one parameter at a time
- Data from seven countries were considered in the test, namely Austria, Denmark, East Germany (the former GDR), Greece, Poland, Sweden, and United Kingdom
- Data used in the test are all related to the RAINS Official Energy Pathway scenario and the year 2000

The focus has been on data and calculations concerning sulphur as pollutant since this is of main interest in the current discussions on emission reductions. The four input parameters were regarded by the model developers to be the parameters which affect the cost calculations most. Furthermore, the influence of especially these parameters on cost calculations have been discussed by decision makers. The countries were chosen arbitrary among the European countries, as representatives for different energy structures. However, the results of the survey will not be shown for all countries. Since discussions on emission reductions are related to the Official Energy Pathway projections in the year 2000, it was obvious to focus this analysis on these data as well.

In order to make the sensitivity results most accessible, these data are discussed separately for the three cost calculations included in the analysis.

It should be mentioned that a sensitivity analysis as the one used here shall be considered only as a part of a more comprehensive evaluation procedure. By focusing on the sensitivities of the parameters one gains information only on the robustness of model output. A procedure for a more thorough and complete evaluation of an Integrated Environmental Model is suggested in Chapter 4.

3.2 Cost Coefficients

RAINS calculates cost coefficients and presents them as an estimate related to country, fuel type, abatement option, scenario, and year (see equations (2.1) and (2.2)). The estimates can be seen in ENEM and are presented as values in a table. It is therefore possible to estimate quantitatively the sensitivity of the cost coefficients resulting from input parameter changes.

3.2.1 Approach

In general, the sensitivity, $sens_i$, of an output value, R, to an input parameter, α_i, can be expressed in mathematical terms as:

$$sens_i = \left[\frac{\partial R}{\partial \alpha_i}\right]_{\alpha^o} \tag{3.1}$$

α^0 denotes that the derivatives are evaluated at the original value for the input parameter.

The non-dimensional quantity

$$Sens_i = \left[\frac{\partial R}{\partial \alpha_i}\right]_{\alpha^0} \frac{\alpha_i^0}{R^0} \tag{3.2}$$

is used especially for comparing the sensitivity importance of different inputs irrespective of differing scales or units of measurements. α^0_i and R^0 denotes the nominal values of the input parameter and resulting output value, respectively. α_i, represents the changed parameter value (changed compared to the nominal value), and R the corresponding output response. This sensitivity measure is referred to as relative sensitivity.

Equations (3.1), (3.2) are valid for linear (or approximate linear) response changes and are denoted first-order sensitivities or linear sensitivities. A Taylor series expansion can give the expression for any arbitrary order (see, for example, Ronen, 1988).

The so-called "brute force" method (see, for example, Ronen, 1988) is the simplest way to state a sensitivity measure. The first order sensitivity (3.2) is simply approximated by

$$Sens_i \approx \left[\frac{\Delta R}{\Delta \alpha_i}\right]_{\alpha^0} \frac{\alpha_i^0}{R^0} \tag{3.3}$$

where $\Delta\alpha_i$ denotes the change in the input parameter from the nominal value α^0_i, and ΔR is the responding change of output response from the nominal value R^0.

Here equation (3.3) has been utilised for calculating sensitivity measures.

3.2.2 Results

Equations (2.1) and (2.2) are used in the RAINS calculations for estimating the cost coefficients c_{PJ} and c_{SO2} for all countries and abatement options which require additional investments at the plant site. The effects on cost coefficients of parameter changes do not differ substantially between different countries and abatement options. The results of the test are, therefore, presented for one cost estimate related to use of flue gas desulfurization (FDG) and heavy fuel oil in old (retro) power plants in Denmark.

Tables 3.1 to 3.4 show the results of the sensitivity analysis. The relative sensitivity is estimated by using the brute force equation (3.3).

Table 3.1. Results of the sensitivity test for variations of the boiler size, bs.

Parameter variations in % from nominal value bs (l)	Absolute value of c_{PJ} DEM/PJ	Deviation from nominal value in %	Relative sensitivity
–75	19.03	109	1.46
–50	12.45	37	0.74
–25	10.23	13	0.49
–10	9.48	4	0.41
–1	9.15	0.4	0.44
0	9.11	–	–
1	9.08	0.3	0.33
10	8.84	3	0.30
25	8.44	8	0.37
50	7.98	12	0.25
75	7.66	16	0.21

Table 3.2. Results of the sensitivity test for variations of the capacity utilization, pf.

Parameter variations in % from nominal value pf	Absolute value of c_{PJ} DEM/PJ	Deviation from nominal value in %	Relative sensitivity
–75	35.71	292	3.90
–50	18.02	98	1.96
–25	12.07	32	1.27
–10	10.93	20	1.98
–1	10.05	1	1.04
0	9.11	–	–
1	9.03	0.9	0.81
10	8.30	9	0.88
25	7.32	20	0.79
50	6.14	33	0.65
75	5.29	42	0.56

Table 3.3. Results of the sensitivity test for variations of the electricity prices, c^e.

Parameter variations in % from nominal value c^e	Absolute value of c_{PJ} DEM/PJ	Deviation from nominal value in %	Relative sensitivity
–75	9.01	0.10	0.015
–50	9.06	0.05	0.011
–25	9.10	0.03	0.013
–10	9.11	0.01	0.011
–1	9.11	0	0
0	9.11	–	–
1	9.11	0	0
10	9.12	0.01	0.011
25	9.14	0.02	0.009
50	9.17	0.06	0.013
75	9.19	0.08	0.012

Table 3.4. Results of the sensitivity test for variations of the sulphur content of fuel, sc.

Parameter variations in % from nominal value sc	Absolute value of c_{PJ} DEM/PJ	Deviation from nominel value in %	Rel. Sens.	Absolute value of c_{SO2} DEM/kt	Deviation from nominel value in %	Rel. Sens.
–75	9.04	1.8	0.010	22.44	284	3.92
–50	9.07	0.4	0.009	11.00	93	1.92
–25	9.09	0.2	0.009	7.63	34	1.33
–10	9.10	0.1	0.011	6.31	11	1.09
–1	9.11	0	0	5.73	0.7	0.82
0	9.11	–	–	5.69	–	–
1	9.11	0	0	5.62	1	0.82
10	9.12	0.1	0.011	5.17	9	0.91
25	9.13	0.2	0.009	4.53	20	0.79
50	9.16	0.5	0.011	3.81	33	0.66
75	9.18	0.8	0.010	3.27	43	0.35

As a function of variations in the parameter values (represented in the tables as percentage change from the nominal value, which is represented by 0), the absolute values of the cost coefficients (expressed in DEM per PJ or as DEM per tons of sulphur removed) resulting from the change in the specific parameters are displayed. The percentage deviation from the original unchanged RAINS coefficient (denoted by 0) along with the relative sensitivity of the coefficient are also visible in the tables.

If we focus on changes imposed by variations in the boiler size (Table 3.1), it is clear that decreases in input values significantly impact the cost estimate, that is, the cost rises 109% for a –75% change of the boiler size value. Effects of increasing this parameter are less influential, and the cost almost reaches a stable deviation percentage level on 12–16% for the large parameter changes.

Changes in the capacity utilisation has a significantly larger effect on the cost estimate values (see Table 3.2). Responses to parameter changes seem to be close to linear up to ±25% change of the parameter value. For perturbations that exceed this, in the range of –50% to –75%, the impact is more visible; the cost coefficient estimate changes up to 100% to 300%. Again decreases in the parameter value affect the coefficient more than do increases.

A somewhat less influencial impact can be seen in Table 3.3. Here changes in the electricity prices have an impact in cost coefficient deviation of only less than 1%. The effect on cost coefficients of changing the electricity prices must be said to be of negligible influence.

Lastly, Table 3.4 lists information on the effects of changing the sulphur content of fuel. Since this parameter influences both cost coefficients (the coefficient is expressed in DEM per PJ, c_{PJ}, and the coefficient in DEM per kt SO_2 removed, c_{SO2}, (see equations (3.1) and (3.2)) they are both displayed in the table. Impacts on the c_{PJ} coefficient are small and similar to the influence of the electricity prices. There are, on the other hand, considerable changes on the c_{SO2} coefficient, which in trend and size are similar to the tendencies seen of changing the capacity utilisation.

Figure 3.2 shows the relative sensitivities of the cost estimates. For changes in sulphur content of the fuel, relative sensitivities are shown for both coefficients.

Here, it is clear that the four parameters can be divided into three "sensitivity classes": the electricity prices and sulphur content of the fuel (relating to the c_{PJ} coefficient) are both characterised as non-sensitive parameters. The boiler size (implicitly the investment function) can be characterised as a moderately sensitive parameter, while both the capacity utilisation and sulphur content of the fuel (related to the c_{SO2} coefficient) are said to be sensitive parameters.

Furthermore, it must be concluded that cost coefficients are more dependent on, and sensitive to decreases in these input parameter values. This is to be expected looking on equations (2.1) and (2.2). Small parameter changes (up to ±25% change of the original RAINS value) respond in a close to linear way, while larger parameter changes have a more severe impact on the estimates.

The further analysis includes only the sensitive characterised parameters: the capacity utilisation and sulphur content of the fuel.

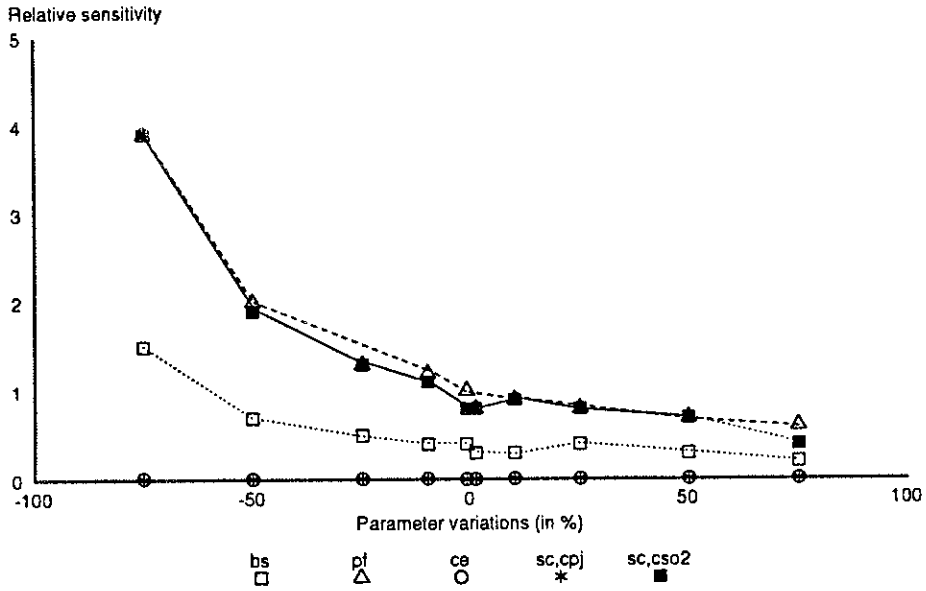

Figure 3.2. Relative sensitivities of the selected input parameters as a function of the percentage of variations from the nominal input value.

3.3 Cost Curves

Cost curves are constructed automatically by RAINS. All the individual cost coefficients (each representing a different control option) are firstly computed, and then applied to the actual amount of energy consumption being controlled in the scenario. The abatement costs are then calculated (corresponding to equation (2.7)). The theoretical options are ranked so emissions are first abated using the combination of abatement technology, fuel type, and economic sector with the lowest marginal costs. Then, a sort of cost optimal least cost solution is found. Typically, the curve consists of about 26 to 29 different options (estimates) dependent on the country. The marginal cost coefficients (equations (2.1) and (2.2)) are used mainly for the ranking curve construction procedure. The basic presentation of cost curves is in the form of national cost curves that represent the total annual costs of abatement versus remaining amount of sulphur that possibly can be removed in the specific energy scenario. The curves are presented in a graphical form in RAINS.

3.3.1 Approach

Testing the cost curves in terms of sensitivity implies basically four aspects to be considered. These are

- the change in single cost estimates
- the number of elements (cost coefficients) which are changed and used in the cost curves
- the energy structure that is assumed for the individual countries
- the sequential order of the changed cost coefficients that form the curve

Each of these points influence the structure and slope of the curves and must be kept in mind when analysing them.

In practice, the changed cost coefficients, reported on in section 3.2.2 were used as a basis for compiling the national cost curve. For every parameter change, a corresponding cost curve was calculated by RAINS. It should be noted that the changes in the capacity utilisation and sulphur content of the fuel influence a varying number of cost coefficients. Changes in the capacity utilisation influence all coefficients representing the Power Plant sector (for all fuel types as old and new plants) which in total means 4 to 6 segments dependent on the country. Changes in the sulphur content of the fuel influence all coefficients representing refineries, power plants, and industry (all fuel types as old and new plants) in total approximately 13 to 16 segments. Additionally, changes in sulphur content of the fuel also influence the curve through the sulphur emission estimates which naturally are calculated using information about the sulphur content of the fuel (see equations (2.10) and (2.11)).

A sensitivity measure corresponding to equation (3.3) cannot be determined. The evaluation of sensitivities will be mainly in graphical form where curves are shown corresponding to different input parameter changes along with the nominal unchanged RAINS curve.

3.3.2 Results

Unchanged nominal RAINS cost curves are depicted in Figures 3.3 and 3.4 for the 7 countries included in the sensitivity test.

In the following the countries are section divided into three groups each representing a different energy structure and therefore differing amounts of sulphur to be abated. Austria, Denmark, and Sweden are all countries with a relatively low percentage of removable sulphur emission. Greece has a comparably much higher emission to abate, and in percentage, for a much lower price than the above three countries. Lastly, the former East Germany, Poland, and United Kingdom are countries with approximately fivefold as much sulphur to possibly remove as Greece. It should be noted that the number of relatively cheap abatement options in the different countries varies (the points on the low end of the curves). Greece, the former East Germany, Poland, and to a certain extent United Kingdom have relatively few cheap abatement options, and a large step in terms of costs and remaining sulphur to the more expensive second group of options. This could possibly affect optimisation results (see section 3.4).

To limit the number of figures to be shown and commented on in the following, only curves for Denmark, Poland, and Greece will be shown as representatiing each energy structure group. Results of the calculations can be seen in Annex 2 in terms of absolute values for the national cost curves. Due to the large amount of data, these are not displayed for the remaining countries.

Figures 3.5 to 3.7 show cost curves for changes in the capacity utilisation in the range from 0% to +75% of the nominal unchanged RAINS value.

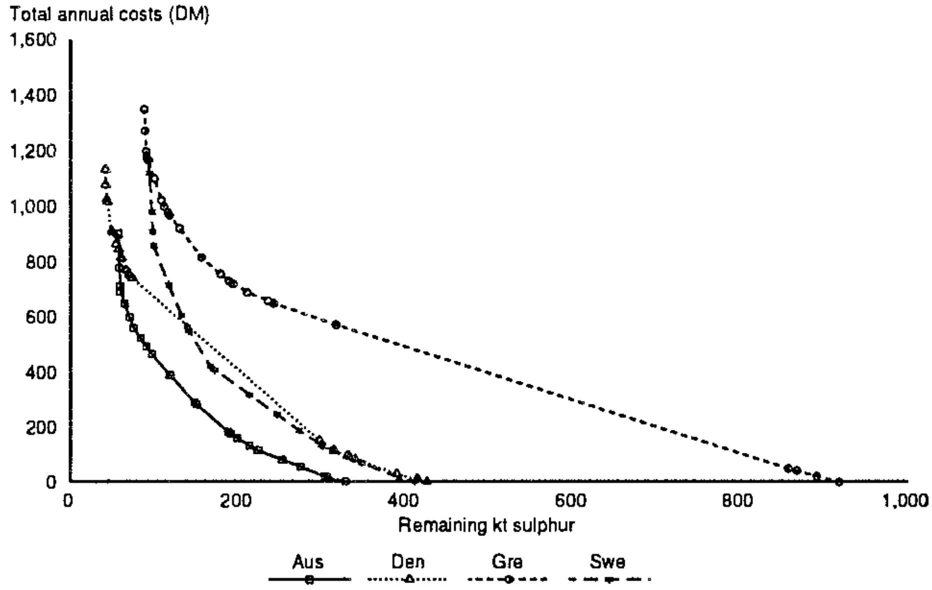

Figure 3.3. National cost curves for the countries Austria (Aus), Denmark (Den), Greece (Gre), and Sweden (Swe).

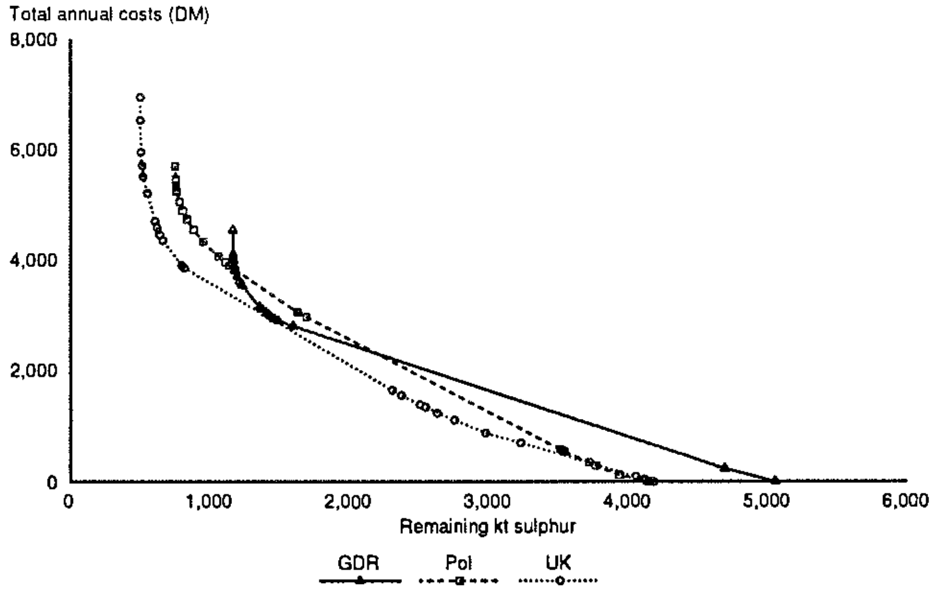

Figure 3.4. National cost curves for the former East Germany (GDR), Poland (Pol) and United Kingdom (UK).

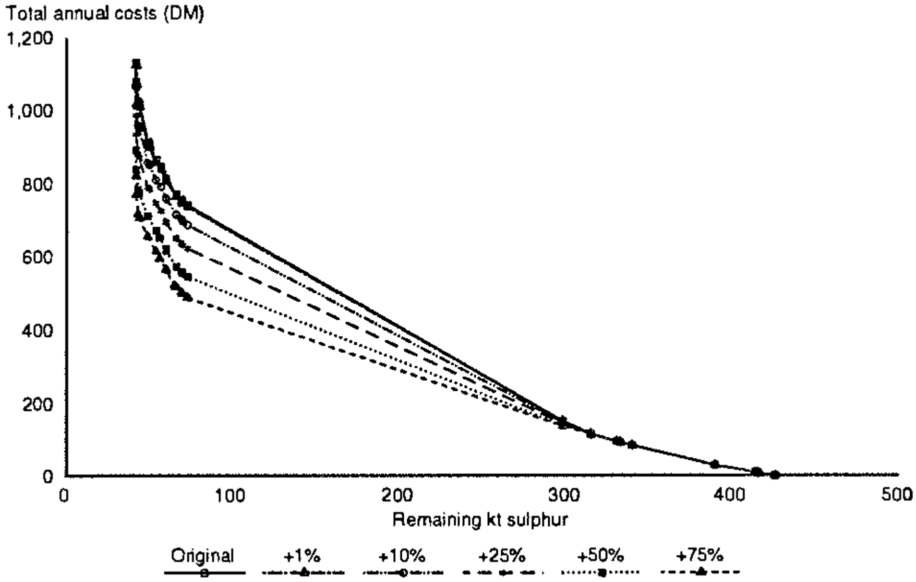

Figure 3.5. Danish national cost curves for changes in the capacity utilization in the range from 0% to 75% of the nominal RAINS value.

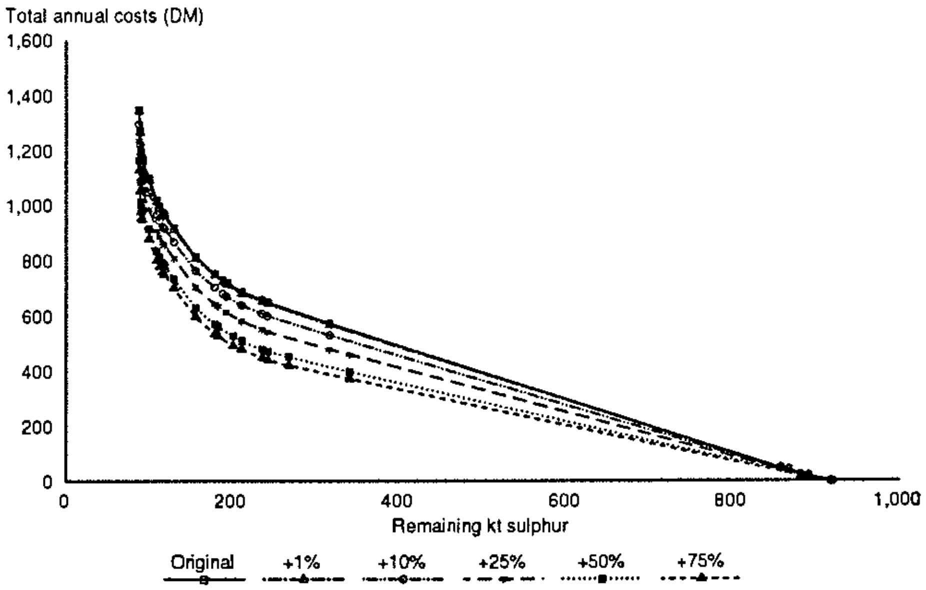

Figure 3.6. National cost curves for Greece for changes in the capacity utilisation in the range from 0% to 75% of the nominal RAINS value.

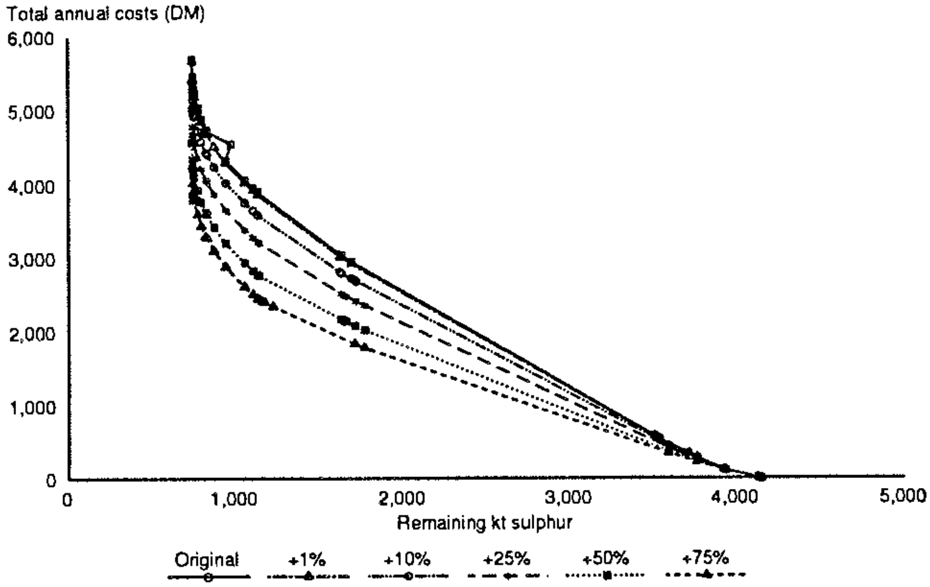

Figure 3.7. Polish national cost curves for changes in the capacity utilisation in the range from 0% to 75% of the nominal RAINS value.

For all three countries, the curves originating from input parameter changes are below the nominal RAINS curve. The first estimates associated with the cheapest abatement options (the lowest end of the curves) are unchanged. When changes do occur, they can be attributed to changes in estimates in the so-called second group of cost estimates (the steepest end of the curves). The few cost estimates affected by the parameter changes gives the changed slope of the curves where single curve values can be changed up to 50%. End points (corresponding to full abatement) are only approximately 10% lower than for the nominal RAINS curve. The curves from Greece seem to be slightly less influenced by the changes.

In Figures 3.8 to 3.10 the corresponding cost curves are shown for changes in the capacity utilisation of 0% to –75% of the nominal RAINS value.

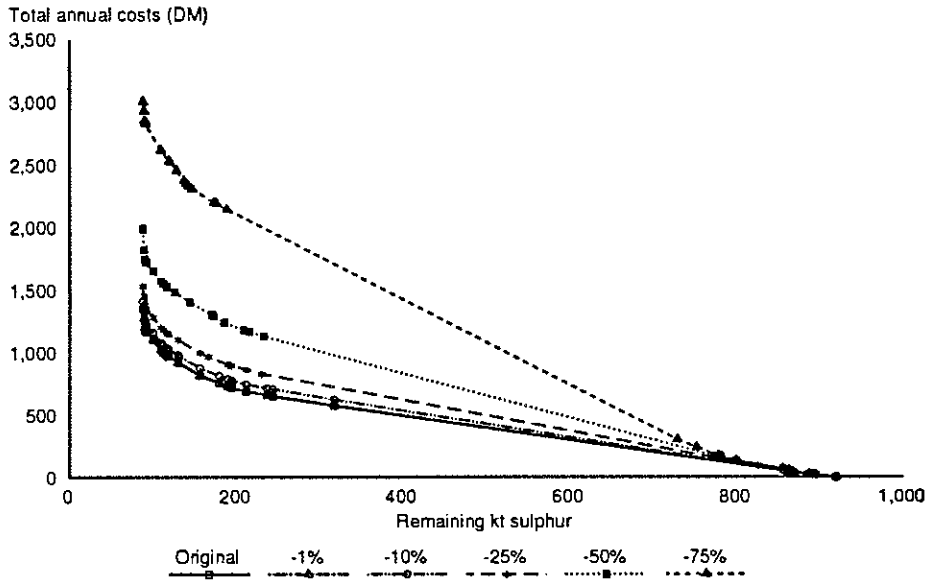

Figure 3.8. Danish national cost curves for changes in the capacity utilisation in the range from 0% to –75% of the nominal RAINS value.

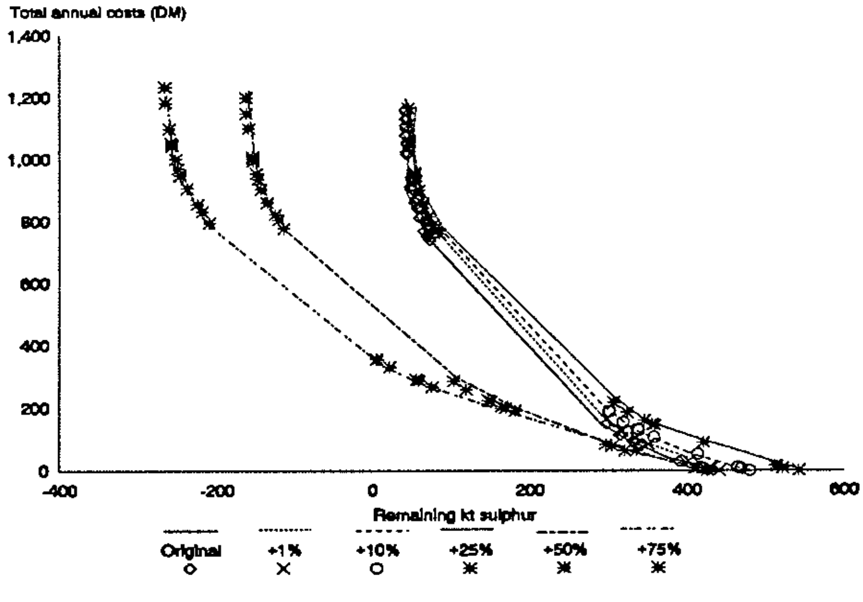

Figure 3.9. National cost curves for Greece for changes in the capacity utilisation in the range from 0% to –75% of the nominal RAINS value.

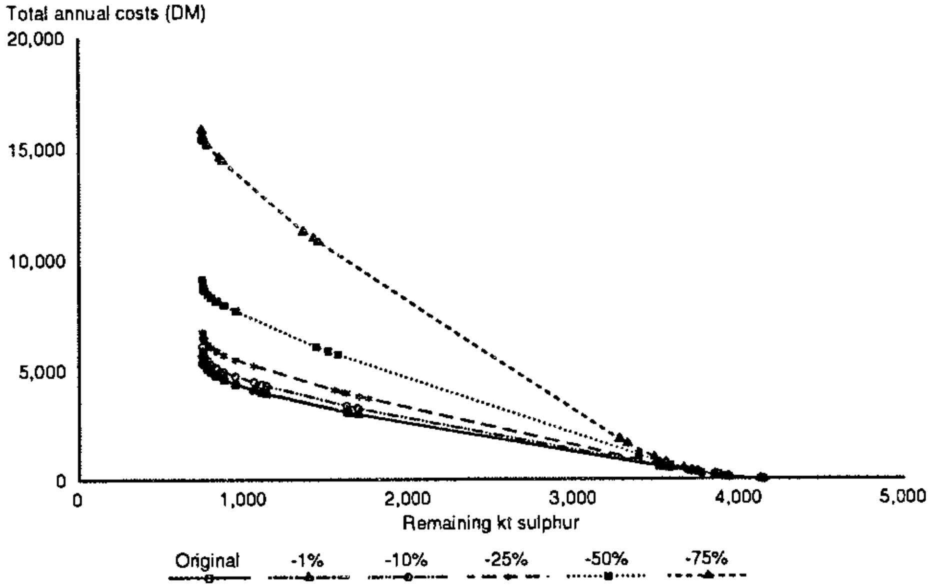

Figure 3.10. Polish national cost curves for changes in the capacity utilisation in the range from 0% to –75% of the nominal RAINS value.

The overestimate of cost coefficient values seen in section 3.3.1 clearly results in curves with higher values than the nominal RAINS curve. For Denmark, Poland, and Greece, it is evident that the changes of –50% and –75% of the capacity utilisation values result in large changes (up to approximately 300% of single values) in the slope of the curves. Again the changes are related mostly to the "second" group of cost estimates.

A somewhat other picture is seen in Figures 3.11 to 3.13 where curves are depicted for changes of sulphur content of the fuel in the range of 0% to 75% of the nominal RAINS values.

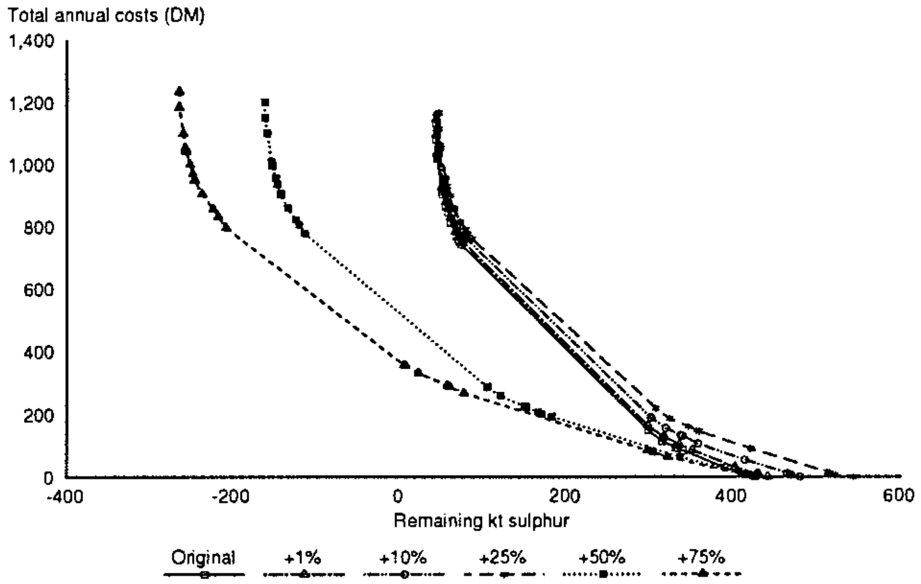

Figure 3.11. Danish national cost curves for changes in sulphur content of the fuel in the range from 0% to 75% of the nominal RAINS value.

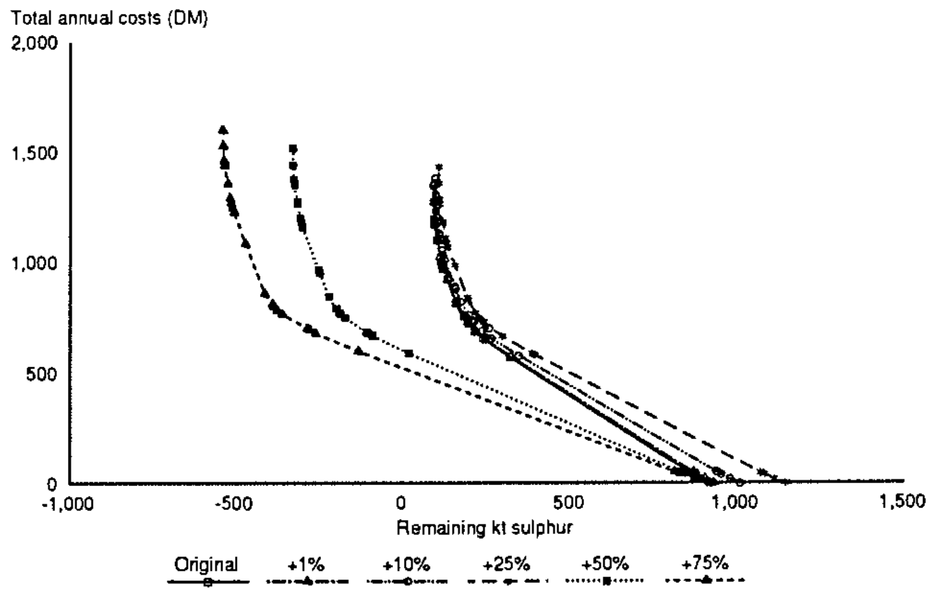

Figure 3.12. National cost curves for Greece for changes in sulphur content of the fuel in the range from 0% to 75% of the nominal RAINS value.

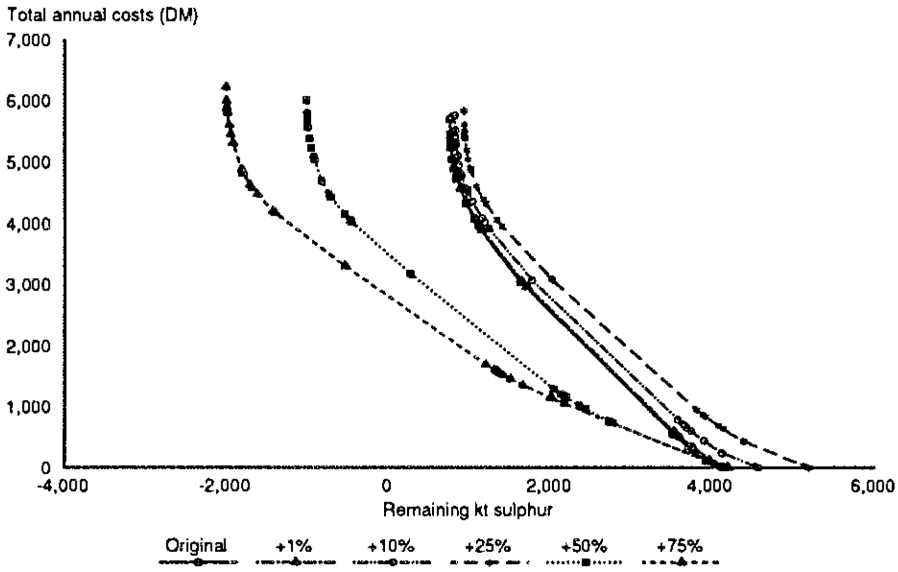

Figure 3.13. Polish national cost curves for changes in sulphur content of the fuel in the range from 0% to 75% of the nominal RAINS value.

For all countries, the changes of +1% to +25% are most evident on the points representing unabated emissions (starting point for the curves). The slopes are not changed much compared to the nominal curve. For Greece, the curve representing the +1% changes runs below the nominal curve, which is different from the other curves (up to +25%) that runs over the nominal curve. Largest impacts are evident on the curves representing +50% and +75%. The structure of these curves and their slope are changed significantly giving negative amounts of removable sulphur. However, all curves show approximately equal cost values. The changes are attributed mostly to changes in sulphur emissions estimates.

The effects of changing sulphur content of the fuel on emission estimates are clearer in Figures 3.14 to 3.16, which represent curves resulting from changes in the sulphur content of the fuel in the range of 0% to −75% of the nominal RAINS value.

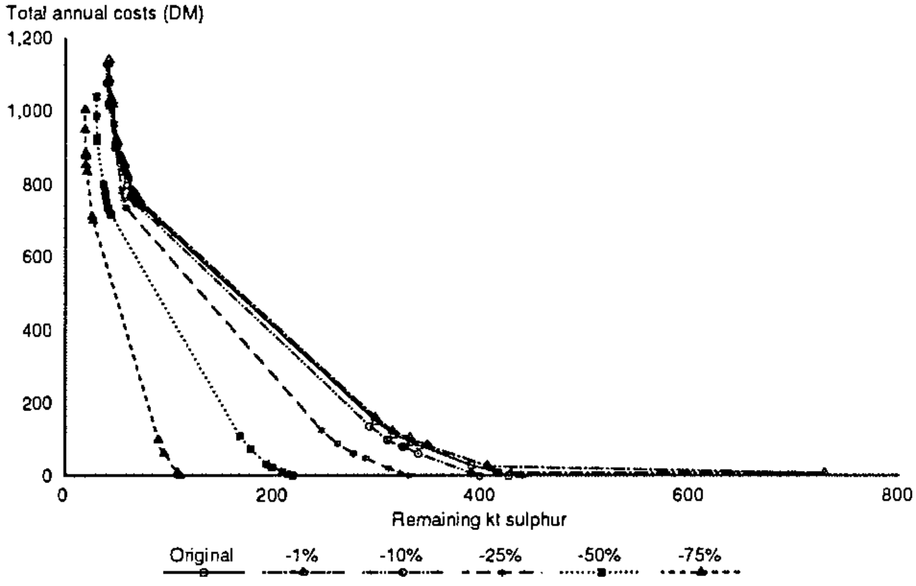

Figure 3.14. Danish national cost curves for changes in sulphur content of the fuel in the range from 0% to –75% of the nominal RAINS value.

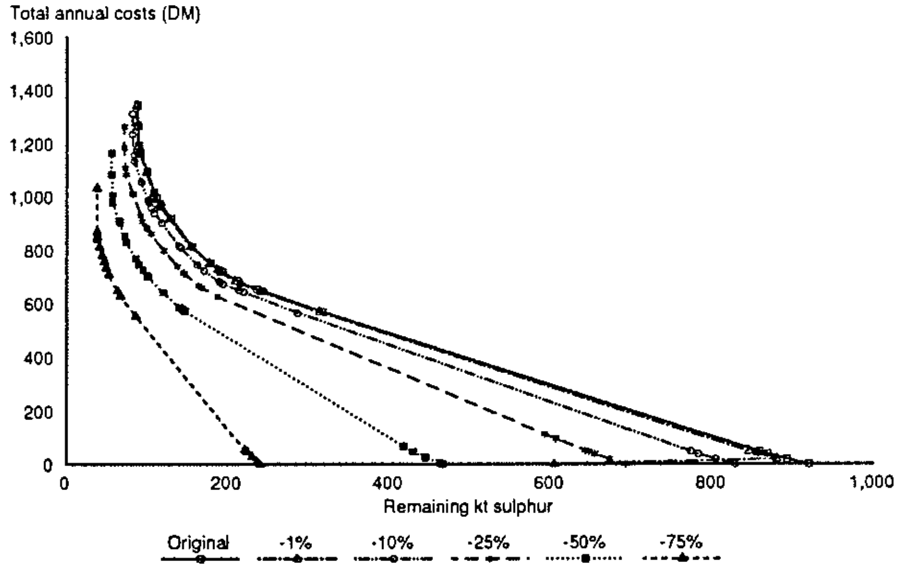

Figure 3.15. National cost curves for Greece for changes in sulphur content of the fuel in the range from 0% to –75% of the nominal RAINS value.

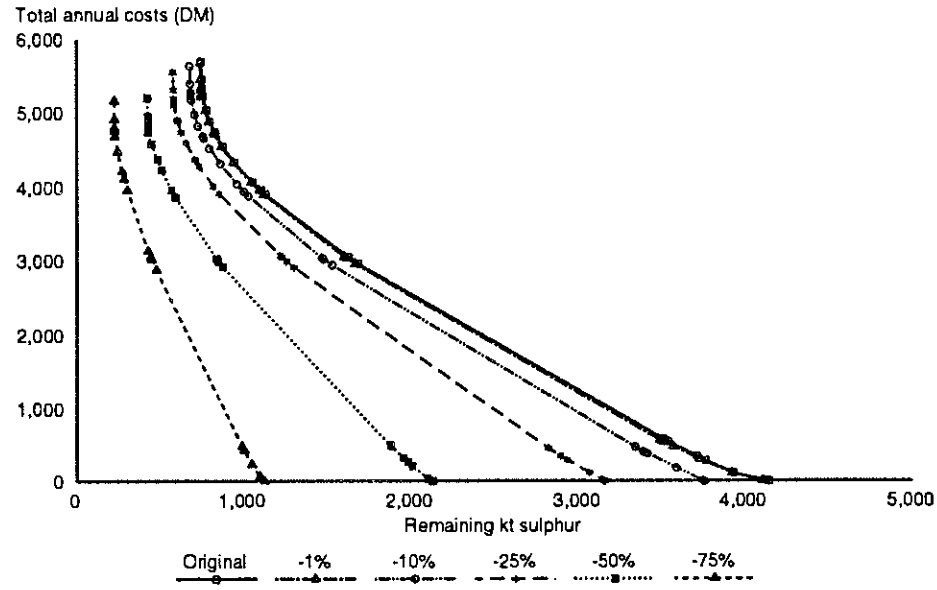

Figure 3.16. Polish national cost curves for changes in sulphur content of the fuel in the range from 0% to –75% of the nominal RAINS value.

Structure and slopes of the curves are heavily affected by these changes. The estimate corresponding to the unabated emission is especially underestimated. The numerical 25%, 50%, and 75% variations in particular change the unabated emission estimate by, respectively, 10%, 50%, and 75%. The cost values are also in this case approximately unchanged compared with the nominal RAINS values. The tendency to underestimate seems to diminish with more expensive abatement options, where also differences in marginal costs are smaller.

Comments on changes in the capacity utilisation parameter. The variations of the cost curves (see Figures 3.3 – 3.8) are closely connected to those imposed on the cost coefficients as seen in section 3.2.2. A relatively few number of point estimates in the curves are affected by the capacity utilisation changes. As expected, the sulphur removal potential (the x-axis value) is unaffected by the variations; only the marginal costs (shown on the y-axis) are affected. However, some sulphur removal potential values seem to be changed somehow when comparing the positions of the single point estimates. This can be explained by the ranking procedure used to construct the curves. When single cost estimates increase or decrease their values, the sequential ranking of these will consequently change also. Changing the sequential ranking of the estimates will naturally also change the position of the single points on the x-axis. However, the beginning (corresponding to zero abatement) and end points (corresponding to full abatement) on the x-axis are unchanged. The impacts on the curves seem to have a certain correlation with the energy structure of the single countries. This can best be seen for the curves representing Poland (Figures 3.7 and 3.10) where the estimates for the power plants are more or less gathered in the expensive end of the curves (steepest end), and where a significant effect of the variations is especially seen for the numerically large estimates.

Comments on changes in sulphur content of the fuel parameters. The marginal costs as well as the sulphur emission for each control option are affected by the imposed changes of the sulphur content of the fuel. For *decreases* in the sulphur content of the fuel, the sulphur emissions for each control option decrease (according to equation (2.10)) while the marginal costs increase (according to equation (2.2) and subsection 3.3.2). For *increases* in sulphur content of the fuel, the trends are reversed. Therefore, the estimates of annual costs are not affected significantly, as the curves also showed. The reason for the changes in the cost curves must be attributed to the strong influence of the remaining sulphur emissions (the x-axis) as the sequential changes of the control options in the curves. The last-mentioned factor influences the structure of the curves and the number of control options in each "control option group"; a cheap option may become an expensive one and thereby be ranked lower in the sequence, or conversely. For the numerically large changes of the parameter, the curves are represented by a smaller number of control options. This is seen as a consequence of the assumption that only a certain percentage of sulphur can be removed, and that some options are disregarded in the curve-construction procedure. These curves become naturally more sensitive to changes in single option values. For the large positive changes of the parameter, it can be seen that the emission estimates become negative. A stop-sequence is obviously omitted in the algorithm to prevent this from happening. However, it should be mentioned that these parameter changes are regarded as being highly unlikely to occur in real-life.

General comments. It can be concluded that the results of section 3.3.2 apply to a great extent to the cost curves as well: cost curves are sensitive to changes in capacity utilisation and sulphur content of the fuel. However, the last-mentioned parameter affects both marginal costs as sulphur emission estimates which result in larger structural changes in cost curves. The larger variations of the parameters especially impose changes in cost curves. The likelihood for such large parameter values should therefore be given some attention. This study should be carried out on a national basis, since the probabilities for such variations most likely will change from country to country. Reports, as for example ELSAM (1991a,b) could be valuable in such studies.

Concerning the performance of these algorithms, the simple figures of total remaining sulphur as total annual costs (see, for example, Annex 2 in the table showing the cost curve figures for Denmark with the nominal unchanged RAINS values) seem to be higher or lower than expected. This is not a very important issue, but it could cause confusion for users of RAINS and scepticism towards the results since these tables can be obtained directly from the cost submodel of RAINS.

3.4 Optimisation Results

Optimisation results are basically influenced by two factors: cost curves that enter into the calculations as constraints, and the atmospheric relations linking source and receptor areas. Here only the influence of cost curves on optimisation results were considered. The influence of the source-receptor relations have already been studied by Lehmann (1991a,b).

3.4.1 Approach

A typical linear optimisation problem was constructed based on demands of minimal overall European economic expenditures. This objective was solved by applying environmental constraints, since this was thought to be a likely problem to be set in practical planning and decision making. The environmental targets entering the optimisation problem can be seen in Table 3.5.

Table 3.5. Environmental target loads (as deposition values) used in the optimisation runs.

Country	Target Load as deposition values kt SO_2
Austria	1.00
Denmark	0.75
Finland	0.60
France	1.50
The Netherlands	1.30
Norway	0.50
Sweden	0.60
Switzerland	0.80
United Kingdom	1.00
Former USSR	2.00

These targets were the first official national deposition targets reported to the ECE (for some countries, i.e., Sweden, the target was reported on in a more aggregated form). However, these values do not necessarily express the current political deposition goals. Therefore, they shall be seen only as examples of probable environmental targets presented for RAINS. It should be noted that four of the countries represented by side constraints also enter the analysis by changed cost curves.

The sensitivity of optimisation results was investigated in practice by using the changed cost curves, originating from parameter variations, as the basis for a series of optimisations. The number of single parameter changes made corresponds to the number of optimisation runs. The changes in optimisation results are an outcome of simultaneous cost curve changes from all seven countries considered in the analysis. Curves from other European countries enter into the optimisation calculations as they are determined by nominal values in the RAINS model.

The focus has been on the results expressed as country costs (and emissions—however, these are not discussed in detail). As a consequence of the many calculations involved and the complicated relationship between the input parameter values and optimisation solutions, it would severely violate the mathematical assumptions to express the sensitivity quantitatively in a manner similar to equation (3.3). The evaluation of the optimisation solutions are, therefore, made by subjective comparisons with the nominal case. The changes in the solutions should be attributed only to variations in the cost input data since the constraints and other variables not directly related to cost calculations have been held constant.

3.4.2 Results

As the basis for the evaluation of the various runs, the optimal solution for unchanged nominal RAINS parameter values can be seen in Table 3.6.

Table 3.6. Results of the optimisation with the nominal, unchanged parameter values. Note that the number and aggregation of countries is related to the RAINS version 5.1

Country	Costs in 10^6 DEM	Emissions (kt SO_2)	Emission reduction compared to 1980 level in %
Albania	0	168.0	-65.4
Austria	727.4	59.0	82.1
Belgium	1209.6	96.0	88.3
Bulgaria	0	1555.2	-53.2
The Czech and Slovak Republics	1966.2	766.3	75.3
Denmark	1171.9	42.1	90.5
Finland	692.3	187.9	67.1
France	2432.2	401.1	88.3
Germany-West	6727.1	378.5	87.9
Germany-East	3808.0	1175.6	76.5
Greece	0	919.2	-77.5
Hungary	635.4	607.4	62.5
Ireland	240.3	75.0	66.7
Italy	3880.0	375.0	90.2
Luxembourg	15.9	6.8	63.5
The Netherlands	1192.9	87.9	81.0
Norway	166.6	41.7	69.4
Poland	5469.4	752.0	80.5
Portugal	0	363.1	-37.8
Rumania	545.5	2558.0	-51.1
Spain	353.8	2272.1	26.9
Sweden	890.7	99.2	80.0
Switzerland	84.8	50.5	59.9
Turkey	0	3254.0	-278.2
United Kingdom	4488.3	655.9	86.4
The Soviet Republics	20047.4	2327.5	88.7
Yugoslavia	2924.2	468.1	60.6

A number of countries, such as Albania, Bulgaria, Greece, Portugal and Turkey, are not planning to invest in abatement options. These countries are allowed to increase their emission level beyond their 1980 levels. Spain is a country with a relatively small reduction and correspondingly a small investment in abatement technologies. The countries with environmental constraints are all to reduce their emissions by a percentage ranging from 59.9% for Switzerland to 90.5% for Denmark. For the rest of the European countries, similar reductions are to be made.

It is clear that the optimisation results depend on the geographical distribution of sources and receptors (see also Lehmann, 1991a). Countries with a specified deposition target and those with a close meteorological relationship are to make relatively high emission reductions—and invest in abatement technologies. Countries relatively far from those with deposition targets may increase emissions without disturbing the optimality criteria.

The following Tables 3.7 to 3.10 show the total annual abatement costs of the optimisation solution for changes in the capacity utilization and sulphur content of the fuel values.

Table 3.7. Variations in optimisation results. Results are related to increases in pf values and to costs of abatement.

	Nominal	1%	10%	25%	50%	75%
Albania	0	0	0	0	0	0
Austria[1]	727.4	725.8	702.5	684.4	667.9	659.5
Belgium	1209.6	1209.6	1209.6	1209.6	1209.6	1209.6
Bulgaria	0	0	0	0	0	0
Czeck and Slovak Republics	1966.2	1966.2	1966.2	1966.2	1966.2	1966.2
Denmark[1]	1171.9	1164.6	1104.3	1007.9	788.5	732.2
Finland	679.3	692.2	702.1	696.5	697.9	701.9
France	2432.2	2432.2	2432.2	2432.2	2432.2	2432.2
Germany W	6727.1	6727.1	6727.1	6727.1	6727.1	6727.1
Germany E[1]	3808.0	3780.2	3554.9	3256.8	2899.9	2963.2
Greece[1]	0	0	0	0	0	0
Hungary	635.4	635.4	635.4	635.4	635.4	635.4
Ireland	240.3	248.1	281.7	133.4	255.9	133.4
Italy	3880.0	3879.9	3874.9	3875.8	3868.8	3908.3
Luxem-bourg	15.9	15.9	15.9	15.9	15.9	15.9
Nether-lands	1192.9	1192.9	1192.9	1192.9	1192.9	1192.9
Norway	166.6	166.6	166.6	166.6	166.6	166.6
Poland[1]	5469.4	5426.8	4521.5	4535.3	3862.2	3479.9
Portugal	0	0	0	0	0	0
Romania	545.5	546.3	775.4	591.6	636.8	634.6
Spain	353.8	353.8	353.8	353.8	353.8	353.8
Sweden[1]	890.7	888.7	871.8	855.6	826.9	807.3
Switzerland	84.8	84.8	84.8	84.8	84.8	84.8
Turkey	0	0	0	0	0	0
United Kingdom[1]	4488.3	4461.9	4639.4	4206.3	3998.5	3906.3
Former USSR	20047.3	20047.2	20037.3	20044.6	20036.9	20037.0
Former Yugoslavia	2924.2	2924.2	2924.2	2924.2	2924.2	2924.2

[1] denotes the countries in which the perturbations in cost calculations have been introduced.

Table 3.8. Variations in optimisation results. Results are related to decreases in pf values and to costs of abatement.

	Nominal	−1%	−10%	−25%	−50%	−75%
Albania	0	0	0	0	0	0
Austria[1]	727.4	723.6	761.9	829.5	957.4	1415.2
Belgium	1209.6	1209.6	1209.6	1209.6	1209.6	1209.6
Bulgaria	0	0	0	0	0	0
Czeck and Slovak Republics	1966.2	1966.2	1966.2	1966.2	1966.2	1966.2
Denmark[1]	1171.9	1179.4	1254.8	1397.9	1860.3	2765.9
Finland	679.3	692.2	699.9	700.6	692.2	687.4
France	2432.2	2432.2	2432.2	2432.2	2432.2	2432.2
Germany W	6727.1	6727.1	6727.1	6727.1	6727.1	6727.1
Germany E[1]	3808.0	3836.5	4119.1	4712.3	6494.2	11259.0
Greece[1]	0	0	0	0	0	0
Hungary	635.4	635.4	635.4	635.4	635.4	635.4
Ireland	240.3	228.3	281.7	281.7	281.7	281.7
Italy	3880.0	3880.0	3909.7	3902.9	3911.9	3893.8
Luxem-bourg	15.9	15.9	15.9	15.9	15.9	15.9
Nether-lands	1192.9	1192.9	1192.9	1192.9	1192.9	1192.9
Norway	166.6	166.6	166.6	166.6	166.6	166.6
Poland[1]	5469.4	5508.2	5413.3	6032.0	3818.0	15760.1
Portugal	0	0	0	0	0	0
Romania	545.5	551.0	1335.1	1171.9	545.1	800.5
Spain	353.8	353.8	353.8	353.8	353.8	353.8
Sweden[1]	890.7	892.7	913.7	969.1	1118.5	1612.3
Switzerland	84.8	84.8	84.8	84.8	84.8	84.8
Turkey	0	0	0	0	0	0
United Kingdom[1]	4488.3	4516.0	4754.5	5199.5	7022.4	11835.1
Former USSR	20047.3	20047.2	20044.7	20044.3	20045.9	20046.3
Former Yugoslavia	2924.2	2924.2	2414.3	2520.9	2924.2	2683.5

[1] *denotes the countries in which the perturbations in cost calculations have been introduced.*

Table 3.9. Variations in optimisation results. Results are related to decreases in sc values and to costs of abatement.

	Nominal	1%	10%	25%	50%	75%
Albania	0	0	0	0	0	–
Austria[1]	727.4	713.3	714.2	680.8	598.3	–
Belgium	1209.6	1209.6	1199.2	1209.6	1554.0	–
Bulgaria	0	0	0	0	0	–
Czeck and Slovak Republics	1966.2	1966.2	1966.2	1966.2	1966.2	–
Denmark[1]	1171.9	1168.6	1155.8	756.8	750.6	–
Finland	679.3	683.3	689.5	663.5	767.0	–
France	2432.2	1400.9	1053.6	1053.6	1053.6	–
Germany W	6727.1	6727.1	5937.3	5887.6	4864.1	–
Germany E[1]	3808.0	3808.9	3801.2	3022.4	2935.7	–
Greece[1]	0	0	0	0	0	–
Hungary	635.4	635.4	635.4	635.4	635.4	–
Ireland	240.3	133.4	133.4	101.8	133.4	–
Italy	3880.0	4031.0	4090.8	4090.8	4090.8	–
Luxem-bourg	15.9	15.9	15.9	15.9	15.9	–
Nether-lands	1192.9	1192.9	1192.9	1192.9	1623.8	–
Norway	166.6	166.6	166.6	91.6	91.6	–
Poland[1]	5469.4	5450.1	4569.8	4445.6	2708.5	–
Portugal	0	0	0	0	0	–
Romania	545.5	646.9	483.7	0	0	–
Spain	353.8	353.8	353.8	353.8	314.4	–
Sweden[1]	890.7	1055.8	1026.3	976.8	370.9	–
Switzerland	84.8	84.8	96.3	101.0	139.2	–
Turkey	0	0	0	0	0	–
United Kingdom[1]	4488.3	4467.5	4256.5	3907.9	3300.5	–
Former USSR	20047.3	20034.4	20028.5	20047.1	20066.2	–
Former Yugoslavia	2924.2	2924.2	2924.2	2904.9	2564.1	–

[1] *denotes the countries in which the perturbations in cost calculations have been introduced.*

Table 3.10. Variations in optimisation results. Results are related to increases in sc values and to costs of abatement.

	Nominal	–1%	–10%	–25%	–50%	–75%
Albania	0	0	0	119.9	–	–
Austria[1]	727.4	713.3	623.3	800.4	–	–
Belgium	1209.6	1209.6	1209.6	1701.3	–	–
Bulgaria	0	0	0	0	–	–
Czeck and Slovak Republics	1966.2	1966.2	2300.2	2900.1	–	–
Denmark[1]	1171.9	1175.2	1169.6	1188.8	–	–
Finland	679.3	702.0	685.5	1293.3	–	–
France	2432.2	2432.2	2432.2	4342.1	–	–
Germany W	6727.1	6727.1	6727.1	8665.6	–	–
Germany E[1]	3808.0	3807.3	3814.5	4794.1	–	–
Greece[1]	0	0	0	0	–	–
Hungary	635.4	635.4	635.4	892.0	–	–
Ireland	240.3	281.7	281.7	392.6	–	–
Italy	3880.0	3878.5	3893.7	4090.8	–	–
Luxem-bourg	15.9	15.9	18.9	193.2	–	–
Nether-lands	1192.9	1192.9	1623.8	1137.6	–	–
Norway	166.6	166.6	166.6	324.5	–	–
Poland[1]	5469.4	4752.9	5549.4	6040.0	–	–
Portugal	0	0	0	134.8	–	–
Romania	545.5	791.1	2277.5	3068.1	–	–
Spain	353.8	353.8	353.8	3122.0	–	–
Sweden[1]	890.7	1067.5	1038.6	1398.0	–	–
Switzerland	84.8	84.8	84.8	139.2	–	–
Turkey	0	0	0	0	–	–
United Kingdom[1]	4488.3	4481.9	5205.1	7537.9	–	–
Former USSR	20047.3	20027.6	20028.3	20543.6	–	–
Former Yugoslavia	2924.2	2924.2	2386.0	4033.2	–	–

[1] *denotes the countries in which the perturbations in cost calculations have been introduced.*

Comments on changes in the capacity utilisation parameter. In general the variations of capacity utilisation do not substaintially change the optimisation pattern as seen in Table 3.6. In order to get a better overview of the changes which are seen, Table 3.11 shows the countries for which changes in cost estimates are imposed by the variations in the capacity utilisation parameter (both for de- and increasing values).

Table 3.11. Countries for which optimisation results (in costs) changes with variations in the capacity utilisation.

Country	Nominal cost value	Minimum value	Corresponding change in pf values	Maximum value	Corresponding change in pf values
Austria	727.4	659.5	+75%	1415.2	-75%
Denmark	1171.9	732.2	+75%	2765.9	-75%
East Germany	3808.0	2963.2	+75%	11259.0	-75%
Ireland	240.3	133.4	+25%, +75%	281.7	–10%, –25%, –50%, –75%
Poland	5469.4	3479.9	+75%	15760.1	–75%
Romania	545.5	545.1	–50%	1335.1	–75%
Sweden	890.7	807.3	–75%	1612.3	–75%
United Kingdom	4488.7	3906.3	+75%	11835.1	–75%
Former Yugoslavia	2924.2	2413.3	–10%	2924.2	–50%

The table states the nominal values of the optimisation, the minimum, and maximum values and the percentage changes of the parameter for which the minimum or maximum value was found.

It is clear that the largest variations in optimisation results are seen for East Germany, Poland, and United Kingdom. The countries all enter the optimisation with changed cost curves as seen in section 3.3. Smaller changes in the optimisation cost estimates are seen for Austria, Denmark, and Sweden which also enter the optimisations with changed cost curves. The last country which has been included in the sensitivity analysis, Greece, is unaffected by the changes and does not at any time enter the optimisation solution. In particular, Ireland, Romania, and the former Yugoslavia also experience a certain variation in cost estimates resulting from the different optimisation runs. Another point to be made is that countries with the imposed changes in capacity utilisation values (and correspondingly in their cost curves) are affected, as could be expected from the results seen in section 3.3; minimal values are obtained for the largest decreases in the parameter, while maxium values in cost estimates are obtained for the largest increases in the parameter. However, there is a clear tendency that the variations in optimisation cost estimates have a country specific correlation. The pattern seen in each country's energy structure in section 3.3 can also be seen in the pattern of the optimisation results: Those countries with relatively large amounts of sulphur to abate are found to make the largest investments in abatement of sulphur emissions to fulfil the deposition targets of the optimization. At the same time these same countries experience the largest variations in optimisation results as a direct result of their variations in cost curves. Also these countries are the ones with most efficient options for abatement and have a close meteorological relationship to the deposition target areas.

For Ireland, Romania, and the former Yugoslavia, the maximum and minimum values of the optimisations are not necessarily the same as for those countries with imposed parameter changes. Minimum values for Romania are in the same run compensated by maximum values in Ireland and the former Yugoslavia. Also the minimum value of the former Yugoslavia is compensated in the same run as a maximum value in Ireland. Clearly these three countries enter the optimisation with some degrees of freedom for which the variations in the cost curves are compensated. Other countries for which no variations in optimisation results were seen (as for example West Germany, Italy, the Netherlands and the former Soviet Union) are closely related by meteorological constraints to the deposition target areas, as a result these results are not changed. Ireland, Romania, and the former Yugoslavia are countries with weaker meteorological relationships and can therefore enter the optimisations with values that in absolute amounts can vary substantially.

Comments on changes in the sulphur content of the fuel parameter. Again the variations imposed by changes of the sulphur content of the fuel have a more substaintial character than has been seen for the capacity utilisation. The countries for which variations are seen in the different optimisation runs resulting from changes in the parameter can be obtained in Table 3.12.

First it should be noted that not all optimisation runs based on the different parameter variations gave a feasible solution. For the decreases in sulphur content of the fuel, the solution for –75% variation of the nominal value became unfeasible. For increases of the parameter value, the +50% and +75% variations gave reasons for reaching unfeasible solutions (due to the negative emissions estimated in the cost curves as seen in section 3.3.1).

In general, the influence of the variations in sulphur content of the fuel do not affect the single country estimates as much as they do for the capacity utilisation variations, but substantially more countries are affected. Only three countries, Bulgaria, Greece, and Turkey are unaffected by the changes. These countries are not included in the nominal RAINS solution and due to the lack of closely interrelated meteorological relationships to the target areas, they are omitted in the optimal solution at any given time. The largest changes in cost optimal estimates are seen in France, West Germany, Poland, Romania, Spain, and United Kingdom. Smaller changes are seen in the Czeck and Slovak Republics, East Germany, and the former Yugoslavia. The rest of the above mentioned countries experience changes of up to only 5% of the nominal cost optimal estimate.

The countries for which the parameter variations are imposed do not experience large variations in the estimated values in spite of the large structural changes seen in section 3.3. This can be explained by the insignificant changes of the costs (points) in the curves due to changes in the parameters (see again section 3.3.1). On the other hand, the relatively large changes in the optimisation results of some countries with close intermeteorological relationships to the target areas is a target area itself or has an energy structure where abatement is relatively cheap to implement.

Results of the changes in sulphur content of the fuel become clearer in the estimates of optimal national emissions. This result naturally affects the costs estimates as well since both factors are included in the goal function and its constraints. This will not be further commmented upon.

Table 3.12. Countries for which optimisation results (in costs) changes with variations in the sulphur content of the fuel.

Country	Nominal cost value	Minimum value	Corresponding change in sc values	Maximum value	Corresponding change in sc values
Albania	0	0	1%, 10%, –1%, –10%, –25%, –50%, –75%	119.9	+25%
Austria	727.4	598.3	–50%	800.4	+25%
Belgium	1209.6	1199.2	–10%	1701.3	+25%
Czeck and Slovak Republics	1966.2	1966.2	1%, –1% –10%, –25% –50%	2900.1	+25%
Denmark	1171.9	750.6	–50%	1188.8	+25%
Finland	679.3	663.5	–25%	1293.3	+25%
France	2432.2	1053.6	–10%, –25%, –50%	4342.1	+25%
East Germany	3808.0	2935.7	–50%	4794.1	+25%
West Germany	6721.1	4864.1	–50%	8665.6	+25%
Hungary	635.4	635.4	1%, 10%, –1%, –10%, –25%, –50%, –75%	892.0	+25%
Ireland	240.3	101.8	+25%	392.6	+25%
Italy	3880.0	3878.5	+1%	4090.8	+25%
Luxem-bourg	15.9	15.9	1%, –1%, –10%, –25%, –50%,	193.2	+25%
Nether-lands	1192.9	1137.6	+25%	1623.8	+10%
Norway	166.6	91.6	–50%	324.5	+25%
Poland	5469.4	2708.5	–50%	6040.0	+25%
Portugal	0	0	1%, 10% –1%, –10% –25%, –50%	134.8	+25%
Romania	545.5	0	–50%	3068.1	+25%
Spain	353.8	314.4	–50%	3122.0	+25%
Sweden	890.7	370.9	–50%	1398.0	+25%
Switzerland	84.8	84.8	+1%, +10% –1%	139.2	+25%
United Kingdom	4488.7	3300.5	–50%	7537.9	+25%
Former Yugoslavia	2924.2	2386.0	+10%	4033.2	+25%

The table states the nominal values of the optimisation, the minimum, and maximum values and the percentage changes of the parameter for which the minimum or maximum value was found.

General Comments on the Optimisation Results. In general, optimisation results are sensitive to variations in the capacity utilisation and sulphur content of the fuel. Optimisation *patterns* do not, however, change significantly, but *single values* may. As a result hereof it must be concluded that the absolute estimates of optimisations allocated to the individual countries should only be utilised carefully. A better way of using the optimization results is to make comparable studies that focus more on differences in the pattern of the solutions than the absolute values.

3.5 Discussion

Some specific comments related to the methodological approach of the total analysis shall be made.

Looking upon the RAINS model as a representative for the Integrated Environmental Models, it was an aim of the analysis to apply the same methodological approach to all the costs considered here. This aim shall be seen as opposed to the commonly used approach where perhaps each of the three cost parts would have been studied by applying three different methodological ideas for the study. It is my perception that the traditional approach often leads to confusion, since individual analyses are commonly based on different assumptions, different methodological angles, different areas of concentration, and different ways of expressing the results of the analyses (see examples in Tables 4.3 and 4.4, Chapter 4). The present sensitivity test shall be seen as an attempt to reduce these aspects of confusion.

Simplicity was another aim of the test. Methodologically, this sensitivity test is easily understood; it is direct, it can be applied by most people with access to the code, and it does not impose large, unnecessary assumptions for a heavy mathematical or numerical instrument which is understood by only few people.

It is a test which can be applied to most models (also the Integrated Models in general) with only few modifications. However, the test has some obvious limitations which should be mentioned:

Firstly, it shall once more be stressed that the test indicates only something about the robustness of the results for a selected range of variations of input parameter values to the calculations. The test does not express anything about the probability of the occurrence of the specific values of the parameters. It was, at the time, not possible for the author to make qualified judgements about the probabilities of the events, and by "guessing" there would be a risk of introducing unnecessary uncertainty into the analysis. "Uncertainty" of cost calculations is, therefore, still an issue to be investigated.

Another point to make clear is the lack of a clear objective value or score which easily expresses the result of the analysis. However, it was not possible to give this, and the conclusions made are interpreted subjectively, and therefore open to criticism. In spite of this, it is the belief of the author that a degree of subjectivity is always present in performing analyses, and that it can be difficult to see to which extent it is applied.

Thirdly, it shall be mentioned that this test deals only with specific technical aspects of points for raising uncertainty. Chapter 4 will present more comments on this aspect, and place an analysis such as this one into a larger framework for model judgements.

Lastly, the analysis has considered only variations of parameters one at a time. However, the author has made a few attempts for judging the effect of changing two parameter values at the same time (the parameters referred to are the capacity utilisation and sulphur content of the fuel). Simultaneous changes in these parameters do not, however, give significantly worsened or changed effects than can be seen from the one-at-a-time variations. The tendencies cancel out and do not become as extreme. These results were performed only for a few parameter values and shall not be reported nor commented upon further here.

In Sørensen (1993a), the limitations of methods for analysing models are discussed further.

3.6 Summary

A sensitivity test of the RAINS models was performed. The focus was put on the calculations related to cost calculations of abatement of sulphur. The idea was to investigate the effects of specific cost coefficients, cost curves, and on the cost results obtained after performing an optimisation resulting from varying single input parameters in calculating these values. Four parameters were considered to have a certain impact on the calculations, namely, the investment function, electricity prices, capacity utilisation, and sulphur content of the fuel. Immediately, the electricity prices parameter could be characterised as a non-sensitive parameter, the investment function as a moderately sensitive parameter, while the capacity utilization and sulphur content of the fuel were each characterised as sensitive parameters.

4 Model Evaluation

Both in analyses addressing single problems such as the acidification problem, and in a multi-problem analysis as required by the sustainability concept, the utilisation of modelling tools for policy analyses demands insight into the accuracy and validity[6] of both the input data and results of the analysis. As a general rule, it is expected that scientists lay out the "facts" of their work making clear what is known and what is not, giving unambigiuous results to be used in the policy-making context. However, the facts of nature, humankind, and their interrelations can usually not be described unambigiously. Furthermore, various fields of science often produce results that seem to be telling different, sometimes contradictory things. Not only do the policy makers suffer from this, but the reputation and credibility of science as well.

In scientific literature the issue of uncertainty of model results has been of concern in recent years. In spite of the almost uncountable number of ideas and methods for treating technical uncertainties, these are only exceptionally applied adequately. This treatment of uncertainty is commonly referred to as model evaluation or a part of a model evaluation. Some of the problems of applying mathematical methods for quantifying uncertainty are illustrated in Chapter 3 (this issue is discussed more intensively in Sørensen, 1993a), where it became clear that Integrated Models often must be treated by a fragmented approach since not all data and calculations are of the same type. However, the explicit treatment of technical uncertainty is not sufficient to secure a consistent analysis, and the use of the results in policy making. The way results and models are presented for users, the relevance of the results for the political issues, and the complexity of the analysis itself are examples of issues that also affect the usability of results. The concept of uncertainty is defined and discussed in Sørensen (1993a,b). Here "uncertainty" is used about the inaccuracies that are associated with model quantities and other model components.

Working with RAINS and similar models, it has become obvious that model evaluations can be performed for two types of target groups: the users and the model operators. The last-mentioned group will, perhaps be interested mostly in how well the model functions, and how to reduce run time by more efficient mathematical and numerical algorithms, and coding language. The users will focus more on how well the results of the model represent reality. "Model evaluation" is here looked upon from the users' point of view.

The fundamental aim of this chapter is to suggest a framework for evaluating Integrated Models. Model evaluation will be defined here in more broadly ranged terms compared to the traditional view. Objective here is to enable the evaluation procedure to be utilised positively by both scientists and policy makers. The RAINS model will also play a central role in this chapter, since the model has been the basis for identifying the points in the evaluation procedure. These are exemplified by the RAINS model. The chapter is based on Sørensen and Vidal, (1993).

4.1 Traditional Aspects

Traditionally, model evaluation implies the performance of one, two, or all three of the points outlined in Figure 4.1. Ideally, the points can be seen as steps in a

6. Both the terms accuracy and validity will be defined later in this chapter

process for a full model evaluation.

The verification of a model is closely related to examining whether or not the model measures relative changes satisfactorily, while the points of validation and analysis are concerned with examining (and quantifying) absolute measures.

- **Verification** where the model's behaviour is checked and calibrated so it behaves as intended. This step usually implies a comparison of the model results with observations of the real system
- **Validation** where the structure of the model is checked if it behaves realistically with an independent set of data not used in developing the model
- **Analysis** where the verified and validated model is analysed and described at points for questions/assumptions. This step implies normally *uncertainty* and *sensitivity* analyses

Figure 4.1. The points of traditional model evaluation (source: Hettelingh, 1990).

Commonly, the analysis part of a model evaluation is regarded as being of the greatest importance and informative value to the users. To perform an ***uncertainty analysis*** implies that a comparison be made of the importance of the relative uncertainties in terms of their relative contributions to uncertainty in the outputs. This may include the following aspects (as suggested by Alcamo and Bartnicki, 1985): the identification of model inherent uncertainties, ranking of uncertainties (according to their importance and level of uncertainty), evaluation of identified uncertainties (basically quantification of the uncertainties), and presentation of the results of the uncertainty analysis in an understandable form. ***Sensitivity analysis*** is used to determine the importance of input parameters, initial conditions, and assumptions on model results by changing them and noting the magnitude of the changes in the results, as already mentioned in Chapter 3. A sensitivity analysis may be regarded as an element of the uncertainty analysis related to identifying and ranking sources of uncertainty.

The practical performance of these steps is highly dependent on the quality and quantity of the assumptions made under the model development, and of data used in the model and availability of data not used in the model (for verification analyses), as well as the structure, complexity, and size of the model. In literature a full evaluation is seldom reported.

These traditional evaluation aspects have developed along with the development of models (though with a certain time-lag). It is obvious to the author that these evaluation aspects can be applied to strongly compartmentalised models closely connected with describing a relatively well-bounded, structured, and well-known problem situation. Working with models as Integrated Models, the process seems to be too formalistic, and lacks aspects which concentrate more on the frame upon which the model is built, and how it applies to the problems of the policy-making context.

4.2 Criteria for Evaluation of Models

In the following the term "model evaluation procedure" is used broadly, put together using criteria which may be understood more as an assessment of the model. Seen from the author's point of view an assessment includes more far-reaching analyses of the sociopolitical processes behind the problem addressed by the models, as well as the social consequences of using the integrated models, and development of alternative approaches (Vidal, 1992).

In the last years, several researchers have reported on an attempt to define abstract criteria for judging the quality and applicability of models. Guariso and Werthner (1989) have operated with five criteria that shall be fulfilled if a model is to be readily accepted by its users. These criteria, together with the experiences noted in the previous chapters, form the basis for the following outline of criteria for model evalation as can be seen in Table 4.1. These criteria for model evaluation shall be understood as steps or points to go through in judging the usability of the model.

Table 4.1. Criteria for evaluating Integrated Environmental Models which are to be used in environmental policy making and management. (Based on Guariso and Wertner (1989)).

Criteria for evaluating Integrated Environmental Models	**Comments**
Endogenic Factors:	
Accuracy	The model should represent reality in a fairly close way – scientific and technical aspects – policy strategies
Robustness	The model should include aspects of flexibility in order to deal with factors which were disregarded or in order to deal with values of other parameters that are open to discussion – scientific and technical aspects – policy strategies
Exogenic Factors:	
Simplicity	The model should include a limited number of variables and parameters
Transparency	The model should have options for modifying model relations and values
Adequacy	The model should communicate with the user in a common language
Usability Factor	
Effectiveness	The model must contribute as much as possible to solving the problem for which it is designed

The grouping of criteria into exogenic, endogenic, and usability factors is accomplished from the perspective that a model consists of a frame or structure (a number of exogenic assumptions) in which data, and mathematical relations are inserted (representing the endogenic assumptions). Additionally, a third factor must be considered when judging the model, namely, the usability of the model in the environment for which it is designed.

The ***exogenic factors***: simplicity, transparency, and adequacy are all terms associated with the main structure or frame upon which the model is developed. The criteria must in fact be dealt with already when developing the model, and cannot necessarily be modified significantly when the model is in use.

The ***endogenic factors:*** accuracy and robustness are terms closely related to judging the behaviour of the model and its results. Here, it typically is the uncertainty and sensitivity analyses which are used to determine the accuracy and robustness of results and model inherent parameters, variables, relationships, etc. The ***usability factor,*** the effectivity, shall here be assumed to state something about the applicability of the model to practical planning and decision making.

If we compare these two factors with the steps in the traditional evaluation procedure (as outlined in section 4.1), the verification, validation, and analysis points are all closely related to the endogenic factors as depicted here. In the following the criteria will be commented upon further and the RAINS model will be judged by applying the criteria to the extent to which it is possible.

4.2.1 Robustness and Accuracy

The endogenic factors are commented upon simultaneously since they share many common features and are closely related to the steps in the traditional evaluation process, as outlined in section 4.1. The criteria of *accuracy* implies that the model and its results should be judged whether it represents reality sufficiently on both scientifical as technical aspects as well as on the policy strategies which may be included in the model. The most influential and important scientific and technical aspects may be evaluated in terms of measures of uncertainty associated with the structure of the model, data, parameters and variables, and linkages among the submodels. The accuracy of policy strategies to be implemented must be judged on the relevance of the strategies and likelihood of their being implemented in reality. This means that, for example, scenarios should be judged in terms of their relevance to the policy problem which the model is intended to solve. Despite the close connection of the accuracy criteria and the points in the traditional evaluation process, it is the author's experience that the analysis phase (which involves a quantification of uncertain sources) can be applied to only a limited extent. This has more to do with the complexity of applying known methodologies for uncertainty analysis to the large integrated models, than avoidance of the modellers.

Closely connected with the accuracy criteria is the criteria of *robustness.* The model and its results must include a certain level of flexibility towards uncertainty in the scientific/technical model aspects as in the policy strategies. Only in this way can relatively stable results emerge from the Integrated Environmental Models. A sensitivity analysis could in some cases be applied for investigating the robustness of selected variables, parameters open to discussion, and links in the model–as seen in Chapter 3.

Evaluation of RAINS. Many different studies have been made to evaluate accuracy and robustness of the RAINS model. The following Tables 4.2 and 4.3 outline some of the most important tests that have been made along with their main results.

As in the earlier chapter of the report, only those studies that deal with the sulphur part of the model are reported on here.

The individual analyses have concentrated on issues connected to specific assumptions, results of submodels which could be validated, parameter and variable sensitivity and uncertainty analyses, and points which were open to discussion from a scientific and technical point of view. The Modules for Atmospheric Transport and Deposition (this module corresponds to the Critical Loads Assessment Module in the RAINS version 6.0), and Soil Impact are both simplifications of more complex, detailed models, and an extra effort has been put into evaluating this approach. A few parameters and variables have been found and characterised sensitive and/or given a variance estimate.

Table 4.2. Some of the uncertainty and sensitivity analyses made of the Energy/Emissions/Cost Module and the Atmospheric Transport and Deposition Module.

The Energy/Emission/Costs Module		
Focus on	**Analysis Method**	**Findings**
Impact on cost calculations due to parameter changes[1]	Sensitivity study (Brute Force method)	Two parameters significant influence on cost calculations
Atmospheric Transport and Deposition Module		
Focus on	**Analysis Method**	**Findings**
Linearity between source and receptor elements in the matrix[2]	Monte Carlo Simulation	Linearity introduces an approximately 27% variation to the total sulphur deposition estimate
Interannual variability due to specific source-receptor matrices[3]	Sensitivity study (scenario runs—measure by calculation of mean absolute deviation)	Not sensitive to interannual meteorology
Uncertainty of spatial distribution within a country (grid cell emissions)[4]	Gauss's Law on Error Propagation	Small effect
Model comparison (original EMEP model vs. RAINS source-receptor matrix)[5]	Comparison of estimates	RAINS matrix valid on a broad regional scale
Combined effect of uncertainties of dry and wet deposition to the uncertainty in parameters[6]	Confidence intervals	10-25% variation dependent on the receptor site

The Atmospheric Transport and Deposition Module corresponds to the Critical Loads Assessment Module in the RAINS version 6.0

[1] Sørensen (1994c) – the present report
[2] Alcamo and Bartnicki (1985)
[3] Alcamo and Bartnicki (1985)
[4] Alcamo (1987)
[5] Alcamo and Bartnicki (1987)
[6] Alcamo and Bartnicki (1990)

In spite of the many analyses made it is fairly difficult to judge the accuracy and robustness of the various results of the RAINS model. Most of the results used in policy analyses will be those obtained by calculations of more than one submodel (or module). Any uncertainty associated with model results must therefore be regarded as arising from a composite of various sources. It is not possible to judge "the additive" effect of an individually sensitivity or uncertainty analysis, or judge whether some of the single analysis results will be virtually unimportant when viewing the model as a whole. Some of the uncertainty results could be cancelled out by other uncertainties which have the effect of "twisting" the trend in an opposite direction. However, this fragmented analysis approach as seen for the RAINS model is commonly applied to this kind of model.

Table 4.3. Some of the uncertainty and sensitivity analyses made of the Impact Module and the Optimization Module.

	The Impact Module	
Focus on	**Analysis Method**	**Findings**
Study of the Forest Soil Submodels' forcing functions, parameter values, and initiation variables[7]	Sensitivity study (Conventional study)	2-3 parameters identified having substantial impact on results
Validation of Forest Soil Submodel[8]	Comparison with Swedish soil chemistry data	The model is not for site-specific use
Parameters in the Forest Submodel[9]	Sensitivity analysis (Conventional study)	1 parameter identified as a sensitive parameter
Variables in the Lake Submodel[10]	Monte Carlo Simulation	2 variables have substaintial uncertainty
	The Optimization Module	
Focus on	**Analysis Method**	**Findings**
Properties of the optimisation routine due to the structure of cost curves and optimisation results as function of deposition targets[11]	Sensitivity study (analytical approach of parameter changes)	Deviations of optimisation costs on up to 20%, some sources sensitive to small parameter changes, others not
Influence of cost data, on optimisation results[12]	Sensitivity study (Brute Force Method)	The parameters influence on the single optimisation results but not on the overall solution pattern

[7] Porch *et al.* (1985)
[8] Kauppi *et al.* (1990)
[9] Mäkelä and Schöpp (1990)
[10] Kämäri *et al.* (1990)
[11] Lehmann (1991a,b)
[12] Sørensen (1994c) – the present report

Results of the analyses reported upon in Tables 4.2 and 4.3 are not obtainable by a simple application of the model. These must be regarded as single set of analyses from which the results, approach, and assumptions behind the approach must be remembered by the users themselves.

Within RAINS itself, there are only limited options for expressing uncertainties. The older versions of RAINS had options for selecting of various source-receptor matrices in the calculations so the user could judge whether the interannuality was a substantial effect on which to focus. Another option was the mapping of emission levels in Europe expressed as trajectories (lines representing areas within which the emission levels would be less than or equal to the trajectory value). The trajectories could be represented graphically on the screen by 95%-convergence intervals. However, both options are unavailable in the newly developed version of RAINS (perhaps both options can be investigated implicitly by expert users of the model).

As it is now, RAINS can express uncertainties of model calculations by various scenario runs. The model is relatively flexible in creating user-defined scenarios, and the way the user can try out his/her own ideas. It is the experience of the author that one best obtains a feeling for the robustness of model calculations by trying out many different model runs.

The general major conclusion is that RAINS is relatively *robust* and *accurate* if it is used for regional and country-comparable studies. Unfortunately, the results of the analyses are not explicitly presented in the model, which means that the model users must be aware of the analyses, remember the conclusions, and take them into account themselves when a result of a calculation is presented.

4.2.2 Simplicity

The criteria of *simplicity* implies that the model should have only a limited number of variables and parameters. There are several reasons for this. First of all, it is well known that introducing more complexity in a model structure leads to only a small improvement in the results; above a certain level the complexity increases uncertainty considerably. The model should, therefore, have only as many parameters and variables as are necessary to maintain a certain level of accuracy and robustness in the model results. By keeping the model relatively simple, one also gains in terms of computer time and an understanding of the model and its results (transparency).

Evaluation of RAINS. Developing RAINS through a concept of *simplicity* has been an aim in itself, and this concept has been applied throughout the model. This principle has been used particularly in submodels for Atmospheric Transport and Deposition and the Soil Submodel both of which are represented in RAINS as simplifications of more scientifically and technically complex models, as already mentioned. As a result, the model gains in being more comprehensible and less time consuming in its use, and includes a significantly lower number of parameters, variables, equations, etc. Developing a model through a simplicity principle, one risks that the model does not reflect reality. Analyses that have attempted to cope with this problem (see Tables 4.2 and 4.3) indicate that the single submodels respond satisfactory if one uses the results for regional, country-comparable studies (as opposed to local, site-specific studies).

In fact, the judgement of the simplicity of a model can be regarded as a type of validation or verification study. The whole model can be compared to other models addressing the same or similar problems and the models may be compared in terms of the variables, equations, etc., which are utilised in the model. On comparing the acidification models presented in Chapter 2 with each other, it can be seen that even though the models are developed by different institutions and nations, they still display a certain bias in their structural approach, and the data used in them. The one exception to this is the ACIDRAIN model which is designed from a distinctly different approach. The similarities between the models, apart from ACIDRAIN, can be seen as an expression of a sort of scientific concensus on this simplicity, structure, and output data.

The RAINS model must therefore be regarded as an Integrated Model with a reasonable level of variables and parameters seen from a scientific point of view. Whether or not non-scientists consider the level of simplicity to be satisfactory shall remain an open question.

However, it should be noted that Integrated Environmental Models such as RAINS are exposed to criticism in discussions about the level of detail they contain. Scientists dealing with smaller systems may see the simplistic description of the model as inadequate for describing the system. The level of detail shall therefore be taken into careful consideration in respect to how the model is intended for use.

4.2.3 Transparency

Transparency is considered to be the most important criteria by many people. "Playing" with the model, and modifying variables enables the user to test the model her/him self. In reality, this trial-and-error approach is the only way the user can be able to judge the level of applicability, accuracy and robustness, and relevance in general. An Integrated Environmental Model can include only a limited number of options for modifying the values and relations that are linked to the model structure. Therefore, it is important that model developers as well as model users focus attention on variables, parameters, relations, and linkages which are subject to discussion to define which option to be taken.

Evaluation of RAINS. Considering the *transparency* of the RAINS model, there are limited facilities for the user to change single values as a basis for calculations. These facilities are confined to the scenario-building device and to the input values which must be specified before using the impact models. Defining new scenarios can be made relatively easy assuming that the user has some knowledge of energy and emissions. Providing input values to the impact models demands that the user be relatively familiar with the chemical terms and definitions that are associated with the problem of acidification. It is not possible to build in or modify equations or relations in the submodels and by so doing explicitly change the assumptions behind the model results. Limiting these facilities may be reasonable since results made by different institutions and countries could then become impossible to compare if one assumes a consistent basis.

Understanding the model (results, input values, etc.) may be difficult. Definitions of scientific and technical terminologies cannot be obtained directly within the model.

It may be too much to expect that everything in a model be explained and understood by all users. Therefore a manual is essential, and is always available from large software developing companies. This is not the case with policy analyses models, however. A manual for the RAINS model does exist, but only as a preliminary version which has some basic deficiencies. For example, an index for words or abbreviations used in the model or the results is absent. The manual provides the users with information on the use of the model by going through some typical illustrative examples on problems to be addressed by the model. However, the author is sure that the deficiencies concerning the manual will be corrected in future editions.

4.2.4 Effectiveness

The criterion of *effectiveness* cannot be stated as being exclusively an endo- or exogenic factor and is therefore considered to be a single standing criterion.

It may be obvious that the model should contribute to the solving of the problem in close to optimal (or suboptimal) terms. This is, however, not always the case. For the sake of efficiency, the model must address the problem as it is expressed and perceived by the decision makers or users in general. This perception may deviate from the scientific view on the problem. Only if the model is used for analysing problems that are of relevance, will the model support decision processes. Using models for analyses which are not relevant may increase the complexity of the decision process (one example is the Danish Water Action Plan–see Sørensen, 1994b).

How the effectivity of a model shall be determined may be an open question. Different groups of people are likely to judge the effectivity differently. Here the criteria is considered in terms of the way the model contributes to the discussions of the decision-making processes and the level of implementing the strategies identified by the model in real life.

Evaluation of RAINS. Since negotiations on emission reductions still take place, the *effectiveness* of RAINS can be considered only partly. There is no doubt that the model clearly contributes to the international discussions by pointing out special aspects identified by its use. RAINS is utilised both in the negotiations on sulphur emission reductions and in the EC 5th Environmental Action Programme. At this point, it has shown that RAINS is a valuable tool to be used both for raising questions of political interest and for providing scientific support to questions raised by the decision makers.

Whether or not strategies identified by RAINS will ever be implemented in real life shall remain an open question.

4.3 Summary

Work with the RAINS model has been the basis for suggesting six general criteria for evaluating Integrated Environmental Models. The criteria consider both traditional model evaluation aspects of accuracy and robustness as well as aspects that address the usability of the model's aspects, such as simplicity, transparency, adequacy, and effectiveness.

Again, taking the RAINS model as one example of an Integrated Environmental Model, the criteria were applied to it. Considering RAINS in terms of traditional uncertainty and sensitivity analyses, it must be characterised as being relatively accurate and robust if it is used for overall country-comparable studies. There is, however, one major problem that arises when assessing the overall uncertainty of the model, since analyses already applied a focus on single parts of the large model. The simplicity of RAINS is considered to be sufficient given that it is used for regional, country-comparable studies. In terms of transparency, the model has only limited facilities. These are confined to the scenario generation device. This can be seen both as a limitation in the model use but also as a necessary feature in securing consistency for country-comparable studies. The model is operated mainly by experts on various aspects of the acidification problem. To obtain the optimal level of adequacy of the model, one needs a certain basic knowledge and experience with models of this type. Considering the effectiveness, the model clearly contributes to the international negotiations on emission reductions. Whether or not strategies of the model will be implemented in real life remains an open question.

5 Conclusion

The RAINS model has been the focus of this case study on Integrated Environmental Models and their evaluation. RAINS has been presented in terms of structure and scope, and has been compared to similar models. Without doubt, it is the one model which addresses the European acidification problem that has been utilised in most studies.

When analysing the model in terms of parameter sensitivities of the cost calculations, the focus is set on the complexities of performing such analyses in the Integrated Environmental Models. The various structures of the modules and submodels constitute a problem in terms of how the accuracy of such models can be determined in consistent and clear ways. As with the RAINS model, these tests are commonly performed as fragmented analyses that are not gathered into a single conclusion that applies to the whole model as such—and perhaps it is not possible to do so. The problem is recognized in the scientific research forum but remains unsolved. However, the performance of such analyses is insufficient to secure that the models are utilised in the environmental decision-making processes. Therefore, this report suggests six criteria for considering such models. These criteria represent a widening of the traditional concept of model evaluation since it also addresses points of direct relevance for the users of the models.

The stating of overall conclusions on the usability of the RAINS model is a task involving highly subjective viewpoints. Different groups will set different weight on the importance of the criteria. It is the perception of the author that RAINS is a good scientific model addressing the problem of acidification in a direct and relevant way. It is unique in the way it is utilised in the ECE Task Force Groups, and the success of the model is clear. However, on working with this model and other Integrated Environmental Models it becomes clear that these other models have some limitations seen from a user's viewpoint.

Due to the structure and size of the Integrated Environmental Models, it can be difficult to get an overview of their structure and range and the limitations on their usage. Inherent uncertainties and sensitivities can be dealt with mostly through fragmented analyses which leaves questions behind of the assembly of individual results for evaluating the whole model. The large number of different types of variables, parameters, equations, etc., lead to difficulties in expressing uncertainty in explicit terms. These can be dealt with to a certain extent by demanding a high level of flexibility and transparency for the Integrated Environmental Models. On the other hand, introducing a high level of these terms constitutes also a new problem, that is, creating non-comparable results which may focus attention and discussions on these results instead of arriving at solutions to the problems. As most Integrated Environmental Models are structured, they must be operated upon by experts before results are presented to policy makers. Policy makers depend on the objectivity of these results since getting an overview of inherent assumptions, uncertainties, etc., is difficult and time consuming.

In spite of these problems the Integrated Environmental Models can contribute significantly to the process of environmental decision making. They should be looked upon as tools to provide the decision maker with points for identifying possible general solutions to solve the problems.

Some fundamental aspects of this case study shall be emphasised.

First there are the difficulties in characterising and dealing with the technical uncertainties of the Integrated Environmental Models. There is a lack of consensus on the terms to be used in the analyses, how to perform them, and how to express their results. The results are easily seen, as in the case of the RAINS model; a large number of different studies have been made that differ in focus, method used, and ways of expressing the results. It is the belief of the author that such tests do not necessarily raise the level of confidence of the models, but instead raise the level of confusion considering the credibility of the models. Looking upon the various types of model components, the question arises as to whether this sort of testing can be performed in a more consistent way. The sensitivity analyses presented in the report is one attempt to apply one test to various parts of the whole model structure. It was an aim that the test should be understandable, simple, and applicable to all calculations in the test. However, on performing the test it was clear that these aspects are difficult to fulfil. There is a need for guidelines on how to perform the tests, which tests should be used, how they shall be presented for the model users, and whether they shall be incorporated directly into the model.

Secondly, it should be remembered that the difficulty of the problems of endogenic analyses of the models is only one aspect of judging the usability of the model. The aspects of exogenic character and efficiency criteria cannot be investigated through a methodological approach. The sufficient level of these can be determined only in cooporation with the users and other researchers addressing similar problems.

Finally, there are the more general aspects of usage of such models in policy management. For many years, in scientific fields computer models have been considered to be the tool for communicating solutions to scientific problems and information to policy makers or other interested parties. This is without doubt a difficult task since the various forums, the scientific forum and the policy-making forum, have different perceptions of the problems, as well as different perceptions on how the other group behaves in respect to solving the common problems. This case study shows that the use of Integrated Environmental Models is possible. However, it does not say anything about the need for the models in the policy-making forum. This question addresses naturally more fundamental sociological and political aspects and cannot be answered from the experiences gained from this case study.

RAINS is only one example on the uncountable number of models which have been and continually are being developed. The discussions, criticism, and conclusions of this report are applicable to most of the Integrated Environmental Models. RAINS is an example of one of the better and more thorough models.

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A Annex 1: Acidification and the Concept of Critical Loads

In Europe and North America the industrialised development and increased energy consumption have been main causes of the expanding increase in airborne emissions. European emissions of nitrogen (NO_x), sulphur (SO_2), and ammonia (NH_3) have more than doubled since the 1950s.

The pollutants are carried through the atmosphere and there undergo chemical transformations to acid compounds. These compounds are deposited either by rainfalls (as wet deposition) or as gases (dry deposition), and affect receptor areas in various ways. Major effects of the acid deposition are forest dieback, damage of monuments, buildings, etc, eutrophication and acidification of freshwater lakes, and soil.

In the early 1970s "acidification of the environment" was a recognised problem and several research programmes were initiated in order to establish relationships between causes and effects. In the last decades this has led to a great deal of controversy over the potential effects and causes of acidification. However, research studies have established that long-range transport of anthropogenic emissions of sulphur, nitrogen, and ammonia is the main cause of acidification.

Sulphur emissions arise mostly from energy production and consumption and industrialised processes. To a large extent nitrogen emissions are generated through combustion processes as in the transport and electricity sectors. Ammonia is generated almost entirely from agricultural production (animal waste). Sulphur contributes most to the acidity—about 60% of the total acidity in Europe originates from sulphur emissions. Nitrogen and ammonia emissions contribute to the total acidification with 21 and 19%, respectively. Naturally there are major variations among individual countries due to the consequences of a country's composition of energy consumption and agricultural structure.

In order to regulate the acidifying emissions, international protocols have been established. In July 1985 at Helsinki, Finland, a protocol to reduce sulphur dioxide emissions by at least 30% was signed by representatives from 21 countries. This protocol has been renegotiated in 1993/1994. In 1988, the Sofia Protocol was signed by 25 parties. This protocol states that the 10-year average annual nitrogen emission (in the period 1987–1996) should not exceed the 1987 level. There are plans to renegotiate this protocol and establish one for ammonia emission as well.

Atmospheric Transport

After they are emitted, pollutants remain for a period of time in the atmosphere before they are finally deposited to the surface. Due to their chemical properties during this time, suspension pollutants are transported within the air mass and travel considerable distances from the place of the source. However, each substance has a unique chemical behaviour and, therefore, unique transportation properties. Ammonia is the most "local" pollutant with relative high deposition rates near the location of the source. Nitrogen oxides, on the other hand, travel considerable longer distances before they are deposited; the transport behaviour of sulphur lies in between.

Nitrogen and sulphur gases both have a residence time in the atmosphere of one to three days. That means that emissions coming from a single source (for example, a power plant) can be carried with the wind, maybe combine with other chemicals and then be deposited as far away from the source as 1000 kilometres in the form of acid deposition (rain or dry particles). A typical transport distance of sulphur in particular is about 1500 to 3000 kilometres. Oxidised nitrogen travels a comparable distance while a greater part of the reduced nitrogen is deposited considerably sooner at shorter distances (Lövblad *et al.*, 1992). These characteristics may be seen in Figure A.1, which shows average transport distances of the three pollutants.

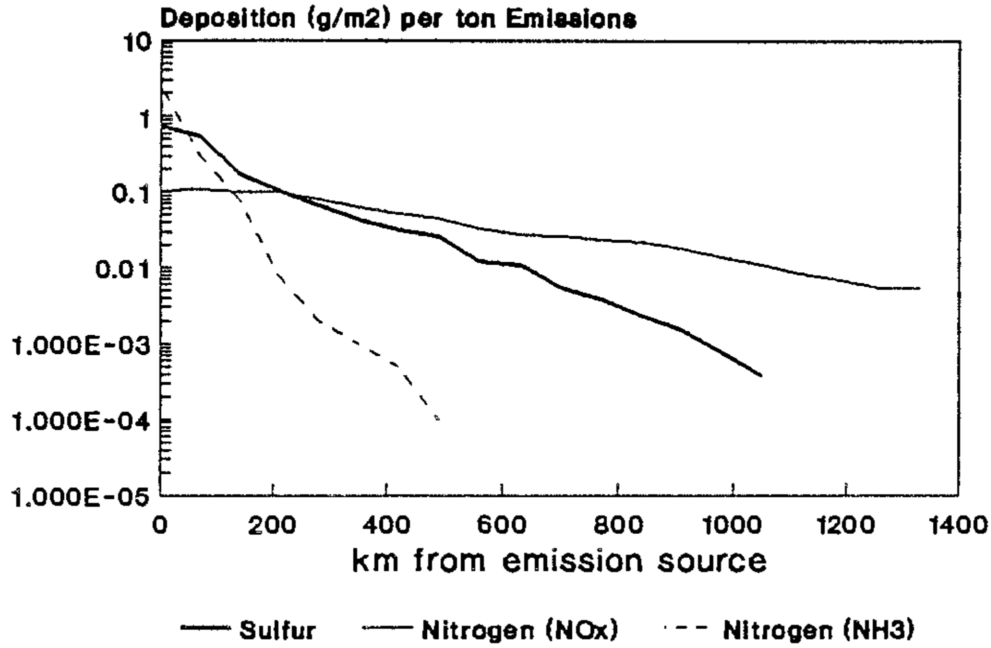

Figure A.1. Average transport distances for nitrogen, sulphur and ammonia (source: Eliassen et al., 1988).

Major depositions of sulphur occur near large emitters in Central Europe but due to long-range atmospheric transport, considerable amounts are also deposited in places such as Scandinavia which have low emissions. Due to atmospheric diffusion processes the deposition pattern for nitrogen compounds is more homogeneous than for sulphur. Ammonia has the highest concentrations near the most intensive agricultural centres.

The long-range transport of air pollutants has major implications on this deposition. Since substances travel typically several hundreds of kilometres before they are finally deposited, acid deposition at specific sites is usually influenced by a large number of emitters. Therefore, in order to decrease the deposition at certain places emission reductions have to be considered at many sources. The problem of acidification is a transboundary one to be solved by all countries in Europe working together.

In the Nordic countries (Norway, Sweden, Finland, Denmark), impacts of the acidification can be detected in soil, surface waters (lakes), and forests as dieback. These impacts are also clear near the centres of emission sources as in the Czech and Slovak Republics, Poland, and southern Germany.

In the attempt to assess impacts of polluting emissions on the ecosystem, and to decide on emission reduction strategies, the concept of critical loads has been developed. This concept is utilised as a basis for comparing deposition levels and for assessing the acidification effect hereof. The critical load concept is a central aspect of the analysis since it is to be attained in internationally adopted long-term policy goals for emission reductions.

Critical Loads for Acidification

In the attempt to assess the effects of emissions on the ecosystem, and decide on emission abatement strategies, the concept of ***critical loads*** has been developed. Critical load is defined as *"A quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge"* (UN-ECE, 1988). Development of the concept has been a scientific response to a general request from politicians needing some sort of measure upon which to base decisions on abatement strategies.

In practice, the critical load value represents an estimate of the maximum level of pollutant at which harmful effects on the particular ecosystem in focus are unlikely to occur. Significant harmful effects are assumed to take place when critical values of chemical compounds in forest soils and freshwater are exceeded.

The critical load value refers to a dose of pollutant deposition exposed to a defined area over a specified period. Typical units are acid equivalent per square kilometre per year or gram acid deposition per square metre per year. These units may represent one or more pollutants.

Five different classes of relative sensitivity of the ecosystem has been chosen (based on research on the Scandinavian region that is considered to exhibit the highest level of acidification). These can be seen in Table A.1.

Table A.1. Relative sensitivity classes and critical load values (Source: Hettelingh et al., 1991)

Relative sensitivity class	Critical load keq per km^2 per year
1	> 160
2	160
3	80
4	40
5	20

The higher the sensitivity class (and lower critical load) the more sensitive is the ecosystem.

A comprehensive work has been performed (and is continuously improved) in all of Europe for establishing a European critical loads map. This work has been carried out under the United Nations Convention on Long-range Transboundary Air Pollution. Critical load values have been determined for the whole area and mapped in EMEP[7] grid cells each of which is approximately 150 km x 150 km). This is made for total acidity, sulphur, and nitrogen.

Values assigned to the grid cells are expressed in terms of percentiles. ***The 5 percentile*** (which is mostly used in practice) ***reflects that 95% of the total area in the cell will be protected by the value*** (if the deposition does not exceed this

7. EMEP: European Monitoring Evaluation Programme.

value). The concept "***exceedance of critical loads***" is used as an indicator of the excess of current deposition loads over the critical load percentile.

Critical loads values may be compared with various deposition levels by the use of the RAINS model (Alcamo *et al.*, 1990). An example showing the exceedance of the 5 percentile critical loads of total acidity is shown in Figure A.2.

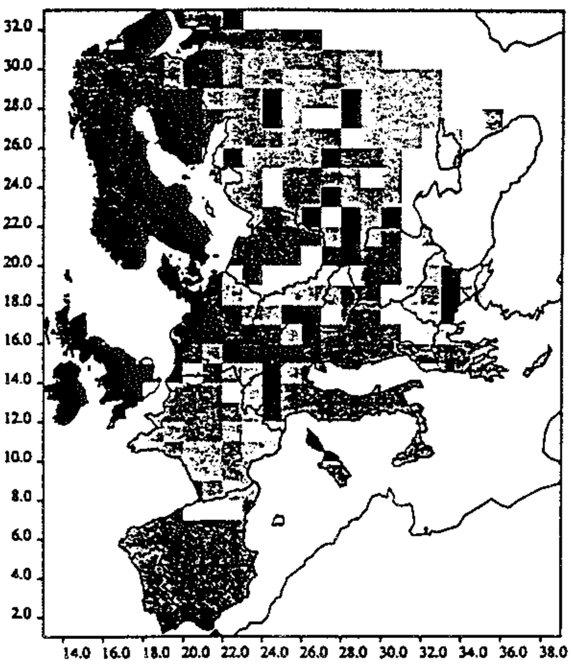

Figure A.2. Exceedance of the 5 percentile critical load values for total acidity in Europe in 1990. (Source: the RAINS model).

The sensitivity of the ecosystem varies with such factors as soil type, climate, type of ecosystem, topography, as well as the length of the time period for exposure of the system. There is far from complete scientific knowledge on deposition effects or synergistic or additive effects with other pollutants. Therefore, the derivation of critical load values is difficult and subject to large uncertainties. Some obstacles are the estimate of depositions, especially for nitrogen; variations in deposition loads between different sites and the relatively large aggregation level (the grid cell sizes); differences in the sensitivity of various ecosystems to depositions; extrapolations of relatively few local monitoring data to generalise a larger area; the comparability of measures and calculations among different institutions and countries for obtaining a European map; and the difficulty in assessing the filtering factor of the different ecosystems on air deposition concentration in order to compare the deposition with the receiving surfaces. However, critical load is an internationally accepted measure for emission-reduction negotiations.

The actual deposition levels, together with technical, social, and economic realities for reducing the emissions, indicate that the emission reductions required to achieve critical load values cannot be implemented by a simple step within a few years. The concept of ***target load*** is therefore used to indicate goals that countries consider may be achieved within a given time frame. Target loads are nationally set, taking into account not only the environmental sensitivity but also technical, social, economic, and political considerations by individual countries.

This value may be set at the same level, higher, or lower than critical loads. Target loads below critical loads may be motivated either by inclusion of a margin safety due to uncertainty in critical load values (to ensure that undamaged ecosystems will remain protected).

B Annex 2: Results of the Sensitivity Analyses

The following pages present computer printouts of the results of the sensitivity analyses of the cost curves reported upon in Chapter 3. Only the printouts representing Denmark, Greece, and Poland are shown.

The pages are organised as follows:

First cost curves of Denmark appear. "Denmark nominal" refers to the cost curve as it is initially represented in the RAINS model. "Denmark pf 75%" refers to the cost curve for Denmark as it is calculated with the parameter value of the capacity utilisation, pf, changed 75% *added to the original value* of the original pf value. "Denmark pf -75%" refers to the cost curve for Denmark as it is calculated with the parameter value of the capacity utilisation, pf, changed -75% *subtracted from the original value* of the original pf value. The tables where the sulphur content of the fuel is changed are shown with "sc" instead of "pf" in the title of the table.

The cost curves for Greece are shown on the following pages. The tables shall be understood in the same way as the for the Danish tables.

Last, the cost curves for Poland are shown. The tables shall be understood in the same way as the for the Danish tables.

Cost Curves for Denmark

Denmark nominal

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill	invest .DM--	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						426	0
FGD Refineries	9	813	7	26	106	416	7
1.0% new HC-PP	1	825	1			415	9
1.0% HC-Domestic	0	825	0			414	9
1.0% old HC-PP	23	825	19			390	29
FGD HF-Industry	50	1076	53	195	623	340	83
1.0% HFO-Domest.	6	1201	8			333	91
1.0% new HFO-PP	1	1201	2			331	93
1.0% old HFO-PP	16	1201	19			315	113
PROCESS-EM. 30%	0	2000	0			315	114
FGD new HC-PP	17	2067	35	178	809	298	149
FGD old HC-PP	224	2630	591	3047	10622	73	740
0.3% MD-Domestic	2	3973	9			70	750
0.3% MD-Industry	1	3973	5			69	756
0.3% MD-Transp.	3	3973	12			66	768
PROCESS-EM. 60%	0	5000	1			66	769
FGD HC-Industry	5	7989	42	142	463	60	811
PROCESS-EM. 80%	0	8000	1			60	813
.15% MD-Domestic	3	8670	30			57	844
.15% MD-Industry	2	8670	19			54	863
.15% MD-Transp.	4	8670	40			50	904
FGD new HFO-PP	0	14216	7	60	284	49	912
FGD old HFO-PP	5	19275	104	767	2765	44	1016
RP Refineries	0	27082	8	60	106	43	1024
RP HF-Industry	1	34118	54	437	623	42	1078
RP HC-Industry	0	312170	51	317	463	42	1130
0.3% MD-Do							
0.3% MD-In							
0.3% MD-Tr							

Denmark pf 75%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						426	0
FGD Refineries	9	813	7	26	106	416	7
1.0% new HC-PP	1	825	1			415	9
1.0% HC-Domestic	0	825	0			414	9
1.0% old HC-PP	23	825	19			390	29
FGD HF-Industry	50	1076	53	195	623	340	83
1.0% HFO-Domest.	6	1201	8			333	91
1.0% new HFO-PP	1	1201	2			331	93
1.0% old HFO-PP	16	1201	19			315	113
FGD new HC-PP	17	1244	21	102	462	298	134
FGD old HC-PP	224	1566	352	1741	6070	73	486
PROCESS-EM. 30%	0	2000	0			73	487
0.3% MD-Domestic	2	3973	9			70	496
0.3% MD-Industry	1	3973	5			69	502
0.3% MD-Transp.	3	3973	12			66	515
PROCESS-EM. 60%	0	5000	1			66	516
FGD new HFO-PP	0	6773	3	34	162	65	520
FGD HC-Industry	5	7989	42	142	463	60	562
PROCESS-EM. 80%	0	8000	1			60	564
.15% MD-Domestic	3	8670	30			56	594
.15% MD-Industry	2	8670	19			54	614
.15% MD-Transp.	4	8670	40			49	654
FGD old HFO-PP	5	9662	52	438	1579	44	706
RP Refineries	0	27082	8	60	106	43	715
RP HF-Industry	1	34118	54	437	623	42	769
RP HC-Industry	0	312170	51	317	463	42	821
0.3% MD-Do							
0.3% MD-In							
0.3% MD-Tr							

Denmark pf 50%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						426	0
FGD Refineries	9	813	7	26	106	416	7
1.0% new HC-PP	1	825	1			415	9
1.0% HC-Domestic	0	825	0			414	9
1.0% old HC-PP	23	825	19			390	29
FGD HF-Industry	50	1076	53	195	623	340	83
1.0% HFO-Domest.	6	1201	8			333	91
1.0% new HFO-PP	1	1201	2			331	93
1.0% old HFO-PP	16	1201	19			315	113
FGD new HC-PP	17	1427	24	119	539	298	137
FGD old HC-PP	224	1802	405	2031	7081	73	543
PROCESS-EM. 30%	0	2000	0			73	543
0.3% MD-Domestic	2	3973	9			70	553
0.3% MD-Industry	1	3973	5			69	558
0.3% MD-Transp.	3	3973	12			66	571
PROCESS-EM. 60%	0	5000	1			66	572
FGD HC-Industry	5	7989	42	142	463	60	614
PROCESS-EM. 80%	0	8000	1			60	616
FGD new HFO-PP	0	8431	4	40	189	60	621
.15% MD-Domestic	3	8670	30			56	651
.15% MD-Industry	2	8670	19			54	671
.15% MD-Transp.	4	8670	40			49	711
FGD old HFO-PP	5	11804	63	511	1843	44	775
RP Refineries	0	27082	8	60	106	43	783
RP HF-Industry	1	34118	54	437	623	42	837
RP HC-Industry	0	312170	51	317	463	42	889
0.3% MD-Do							
0.3% MD-In							
0.3% MD-Tr							

Denmark pf 25%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						426	0
FGD Refineries	9	813	7	26	106	416	7
1.0% new HC-PP	1	825	1			415	9
1.0% HC-Domestic	0	825	0			414	9
1.0% old HC-PP	23	825	19			390	29
FGD HF-Industry	50	1076	53	195	623	340	83
1.0% HFO-Domest.	6	1201	8			333	91
1.0% new HFO-PP	1	1201	2			331	93
1.0% old HFO-PP	16	1201	19			315	113
FGD new HC-PP	17	1683	28	142	647	298	142
PROCESS-EM. 30%	0	2000	0			298	142
FGD old HC-PP	224	2133	479	2438	8498	73	622
0.3% MD-Domestic	2	3973	9			70	631
0.3% MD-Industry	1	3973	5			69	637
0.3% MD-Transp.	3	3973	12			66	650
PROCESS-EM. 60%	0	5000	1			66	651
FGD HC-Industry	5	7989	42	142	463	60	693
PROCESS-EM. 80%	0	8000	1			60	695
.15% MD-Domestic	3	8670	30			57	725
.15% MD-Industry	2	8670	19			54	745
.15% MD-Transp.	4	8670	40			50	785
FGD new HFO-PP	0	10735	5	48	227	49	791
FGD old HFO-PP	5	14779	79	613	2210	44	871
RP Refineries	0	27082	8	60	106	43	880
RP HF-Industry	1	34118	54	437	623	42	934
RP HC-Industry	0	312170	51	317	463	42	986
0.3% MD-Do							
0.3% MD-In							
0.3% MD-Tr							

Denmark pf 10%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						426	0
FGD Refineries	9	813	7	26	106	416	7
1.0% new HC-PP	1	825	1			415	9
1.0% HC-Domestic	0	825	0			414	9
1.0% old HC-PP	23	825	19			390	29
FGD HF-Industry	50	1076	53	195	623	340	83
1.0% HFO-Domest.	6	1201	8			333	91
1.0% new HFO-PP	1	1201	2			331	93
1.0% old HFO-PP	16	1201	19			315	113
FGD new HC-PP	17	1893	32	162	736	298	145
PROCESS-EM. 30%	0	2000	0			298	146
FGD old HC-PP	224	2404	540	2771	9657	73	686
0.3% MD-Domestic	2	3973	9			70	696
0.3% MD-Industry	1	3973	5			69	702
0.3% MD-Transp.	3	3973	12			66	714
PROCESS-EM. 60%	0	5000	1			66	716
FGD HC-Industry	5	7989	42	142	463	60	758
PROCESS-EM. 80%	0	8000	1			60	759
.15% MD-Domestic	3	8670	30			57	790
.15% MD-Industry	2	8670	19			54	810
.15% MD-Transp.	4	8670	40			50	850
FGD new HFO-PP	0	12628	7	55	258	49	857
FGD old HFO-PP	5	17223	93	697	2511	44	950
RP Refineries	0	27082	8	60	106	43	958
RP HF-Industry	1	34118	54	437	623	42	1012
RP HC-Industry	0	312170	51	317	463	42	1064
0.3% MD-Do							
0.3% MD-In							

Denmark pf 1%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						426	0
FGD Refineries	9	813	7	26	106	416	7
1.0% new HC-PP	1	825	1			415	9
1.0% HC-Domestic	0	825	0			414	9
1.0% old HC-PP	23	825	19			390	29
FGD HF-Industry	50	1076	53	195	623	340	83
1.0% HFO-Domest.	6	1201	8			333	91
1.0% new HFO-PP	1	1201	2			331	93
1.0% old HFO-PP	16	1201	19			315	113
PROCESS-EM. 30%	0	2000	0			315	114
FGD new HC-PP	17	2048	35	176	801	298	149
FGD old HC-PP	224	2605	585	3017	10517	73	734
0.3% MD-Domestic	2	3973	9			70	744
0.3% MD-Industry	1	3973	5			69	750
0.3% MD-Transp.	3	3973	12			66	762
PROCESS-EM. 60%	0	5000	1			66	764
FGD HC-Industry	5	7989	42	142	463	60	806
PROCESS-EM. 80%	0	8000	1			60	807
.15% MD-Domestic	3	8670	30			57	838
.15% MD-Industry	2	8670	19			54	857
.15% MD-Transp.	4	8670	40			50	898
FGD new HFO-PP	0	14053	7	60	281	49	906
FGD old HFO-PP	5	19064	103	760	2739	44	1009
RP Refineries	0	27082	8	60	106	43	1017
RP HF-Industry	1	34118	54	437	623	42	1071
RP HC-Industry	0	312170	51	317	463	42	1123
0.3% MD-Do							
0.3% MD-In							
0.3% MD-Tr							

Denmark pf -1%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						426	0
FGD Refineries	9	813	7	26	106	416	7
1.0% new HC-PP	1	825	1			415	9
1.0% HC-Domestic	0	825	0			414	9
1.0% old HC-PP	23	825	19			390	29
FGD HF-Industry	50	1076	53	195	623	340	83
1.0% HFO-Domest.	6	1201	8			333	91
1.0% new HFO-PP	1	1201	2			331	93
1.0% old HFO-PP	16	1201	19			315	113
PROCESS-EM. 30%	0	2000	0			315	114
FGD new HC-PP	17	2087	35	180	818	298	149
FGD old HC-PP	224	2655	596	3078	10730	73	746
0.3% MD-Domestic	2	3973	9			70	756
0.3% MD-Industry	1	3973	5			69	762
0.3% MD-Transp.	3	3973	12			66	774
PROCESS-EM. 60%	0	5000	1			66	775
FGD HC-Industry	5	7989	42	142	463	60	817
PROCESS-EM. 80%	0	8000	1			60	819
.15% MD-Domestic	3	8670	30			57	850
.15% MD-Industry	2	8670	19			54	869
.15% MD-Transp.	4	8670	40			50	910
FGD new HFO-PP	0	14383	8	61	287	49	918
FGD old HFO-PP	5	19490	105	775	2791	44	1023
RP Refineries	0	27082	8	60	106	43	1031
RP HF-Industry	1	34118	54	437	623	42	1085
RP HC-Industry	0	312170	51	317	463	42	1137
0.3% MD-Do							
0.3% MD-In							
0.3% MD-Tr							

Denmark pf -10%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						426	0
FGD Refineries	9	813	7	26	106	416	7
1.0% new HC-PP	1	825	1			415	9
1.0% HC-Domestic	0	825	0			414	9
1.0% old HC-PP	23	825	19			390	29
FGD HF-Industry	50	1076	53	195	623	340	83
1.0% HFO-Domest.	6	1201	8			333	91
1.0% new HFO-PP	1	1201	2			331	93
1.0% old HFO-PP	16	1201	19			315	113
PROCESS-EM. 30%	0	2000	0			315	114
FGD new HC-PP	17	2281	39	198	899	298	153
FGD old HC-PP	224	2906	653	3386	11802	73	806
0.3% MD-Domestic	2	3973	9			70	815
0.3% MD-Industry	1	3973	5			69	821
0.3% MD-Transp.	3	3973	12			66	834
PROCESS-EM. 60%	0	5000	1			66	835
FGD HC-Industry	5	7989	42	142	463	60	877
PROCESS-EM. 80%	0	8000	1			60	879
.15% MD-Domestic	3	8670	30			57	909
.15% MD-Industry	2	8670	19			54	929
.15% MD-Transp.	4	8670	40			50	969
FGD new HFO-PP	0	16161	8	67	316	49	978
FGD old HFO-PP	5	21786	117	853	3074	44	1096
RP Refineries	0	27082	8	60	106	43	1104
RP HF-Industry	1	34118	54	437	623	42	1158
RP HC-Industry	0	312170	51	317	463	42	1210
0.3% MD-Do							
0.3% MD-In							
0.3% MD-Tr							

Denmark pf -25%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						426	0
FGD Refineries	9	813	7	26	106	416	7
1.0% new HC-PP	1	825	1			415	9
1.0% HC-Domestic	0	825	0			414	9
1.0% old HC-PP	23	825	19			390	29
FGD HF-Industry	50	1076	53	195	623	340	83
1.0% HFO-Domest.	6	1201	8			333	91
1.0% new HFO-PP	1	1201	2			331	93
1.0% old HFO-PP	16	1201	19			315	113
PROCESS-EM. 30%	0	2000	0			315	114
FGD new HC-PP	17	2707	46	238	1079	298	160
FGD old HC-PP	224	3457	777	4063	14163	73	937
0.3% MD-Domestic	2	3973	9			70	947
0.3% MD-Industry	1	3973	5			69	953
0.3% MD-Transp.	3	3973	12			66	965
PROCESS-EM. 60%	0	5000	1			66	966
FGD HC-Industry	5	7989	42	142	463	60	1008
PROCESS-EM. 80%	0	8000	1			60	1010
.15% MD-Domestic	3	8670	30			57	1041
.15% MD-Industry	2	8670	19			54	1060
.15% MD-Transp.	4	8670	40			50	1101
FGD new HFO-PP	0	19972	11	80	379	49	1112
FGD old HFO-PP	5	26708	144	1022	3682	44	1256
RP Refineries	0	27082	8	60	106	43	1264
RP HF-Industry	1	34118	54	437	623	42	1318
RP HC-Industry	0	312170	51	317	463	42	1370
0.3% MD-Do							
0.3% MD-In							
0.3% MD-Tr							

Denmark pf -50%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						426	0
FGD Refineries	9	813	7	26	106	416	7
1.0% new HC-PP	1	825	1			415	9
1.0% HC-Domestic	0	825	0			414	9
1.0% old HC-PP	23	825	19			390	29
FGD HF-Industry	50	1076	53	195	623	340	83
1.0% HFO-Domest.	6	1201	8			333	91
1.0% new HFO-PP	1	1201	2			331	93
1.0% old HFO-PP	16	1201	19			315	113
PROCESS-EM. 30%	0	2000	0			315	114
0.3% MD-Domestic	2	3973	9			312	123
0.3% MD-Industry	1	3973	5			311	129
0.3% MD-Transp.	3	3973	12			308	141
FGD new HC-PP	17	3988	68	357	1619	291	210
PROCESS-EM. 60%	0	5000	1			290	211
FGD old HC-PP	224	5113	1149	6095	21245	66	1360
FGD HC-Industry	5	7989	42	142	463	60	1403
PROCESS-EM. 80%	0	8000	1			60	1404
.15% MD-Domestic	3	8670	30			57	1435
.15% MD-Industry	2	8670	19			54	1454
.15% MD-Transp.	4	8670	40			50	1495
RP Refineries	0	27082	8	60	106	49	1503
FGD new HFO-PP	0	31571	17	121	569	49	1521
RP HF-Industry	1	34118	54	437	623	47	1575
FGD old HFO-PP	5	41689	225	1535	5530	42	1800
RP HC-Industry	0	312170	51	317	463	42	1852
0.3% MD-Tr							
FGD new H							
PROCESS-EM							

Denmark pf -75%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						426	0
FGD Refineries	9	813	7	26	106	416	7
1.0% new HC-PP	1	825	1			415	9
1.0% HC-Domestic	0	825	0			414	9
1.0% old HC-PP	23	825	19			390	29
FGD HF-Industry	50	1076	53	195	623	340	83
1.0% HFO-Domest.	6	1201	8			333	91
1.0% new HFO-PP	1	1201	2			331	93
1.0% old HFO-PP	16	1201	19			315	113
PROCESS-EM. 30%	0	2000	0			315	114
0.3% MD-Domestic	2	3973	9			312	123
0.3% MD-Industry	1	3973	5			311	129
0.3% MD-Transp.	3	3973	12			308	141
PROCESS-EM. 60%	0	5000	1			307	143
FGD new HC-PP	17	7829	134	714	3239	290	277
FGD HC-Industry	5	7989	42	142	463	285	319
PROCESS-EM. 80%	0	8000	1			285	321
.15% MD-Domestic	3	8670	30			281	351
.15% MD-Industry	2	8670	19			279	371
.15% MD-Transp.	4	8670	40			274	411
FGD old HC-PP	224	10079	2265	12191	42491	50	2677
RP Refineries	0	27082	8	60	106	49	2685
RP HF-Industry	1	34118	54	437	623	48	2739
FGD new HFO-PP	α	66018	36	242	1134	47	2776
FGD old HFO-PP	5	86176	465	3059	11018	42	3242
RP HC-Industry	0	312170	51	317	463	42	3294
0.3% MD-Tr							
PROCESS-EM							
FGD new H							

Denmark sc 75%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.	invest DM--	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						426	0
FGD Refineries	16	489	8	26	106	409	8
FGD HF-Industry	87	639	56	195	623	321	64
1.0% new HC-PP	16	824	13			305	78
1.0% HC-Domestic	7	824	6			297	84
1.0% old HC-PP	221	824	182			76	266
1.0% HFO-Domest.	16	1201	20			59	287
1.0% new HFO-PP	3	1201	4			56	291
1.0% old HFO-PP	33	1201	40			22	331
FGD new HC-PP	16	1455	23	178	809	6	355
PROCESS-EM. 30%	0	2000	0			5	356
FGD old HC-PP	214	2043	439	3047	10622	-209	795
0.3% MD-Domestic	9	3973	37			-218	832
0.3% MD-Industry	6	3973	23			-224	856
0.3% MD-Transp.	12	3973	49			-237	906
FGD HC-Industry	9	4589	42	142	463	-246	948
PROCESS-EM. 60%	0	5000	1			-246	949
PROCESS-EM. 80%	0	8000	1			-246	951
.15% MD-Industry	2	8669	19			-249	971
.15% MD-Domestic	3	8669	30			-252	1001
.15% MD-Transp.	4	8669	40			-257	1042
RP Refineries	0	12143	6	60	106	-257	1048
FGD new HFO-PP	0	12563	5	60	284	-258	1054
RP HF-Industry	2	16169	44	437	623	-260	1099
FGD old HFO-PP	4	18581	84	767	2765	-265	1183
RP HC-Industry	0	175067	50	317	463	-265	1234
0.3% MD-Do							
0.3% MD-In							
0.3% MD-Tr							

Denmark sc 50%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.	invest DM--	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						426	0
FGD Refineries	14	561	8	26	106	412	8
FGD HF-Industry	75	736	55	195	623	336	63
1.0% old HC-PP	154	824	127			182	191
1.0% new HC-PP	11	824	9			170	200
1.0% HC-Domestic	5	824	4			165	205
1.0% HFO-Domest.	13	1201	16			151	221
1.0% new HFO-PP	2	1201	3			148	224
1.0% old HFO-PP	27	1201	33			120	258
FGD new HC-PP	16	1667	27	178	809	104	285
PROCESS-EM. 30%	0	2000	0			104	286
FGD old HC-PP	218	2247	490	3047	10622	-114	777
0.3% MD-Domestic	7	3973	28			-121	805
0.3% MD-Industry	4	3973	17			-125	823
0.3% MD-Transp.	9	3973	37			-135	860
PROCESS-EM. 60%	0	5000	1			-135	861
FGD HC-Industry	7	5345	42	142	463	-143	903
PROCESS-EM. 80%	0	8000	1			-143	905
.15% MD-Domestic	3	8669	30			-147	936
.15% MD-Industry	2	8669	19			-149	955
.15% MD-Transp.	4	8669	40			-153	995
FGD new HFO-PP	0	13182	6	60	284	-154	1002
RP Refineries	0	15475	7	60	106	-154	1009
FGD old HFO-PP	4	18841	91	767	2765	-159	1100
RP HF-Industry	2	20136	47	437	623	-162	1148
RP HC-Industry	0	205534	51	317	463	-162	1199
0.3% MD-Do							
0.3% MD-In							
0.3% MD-Tr							

Denmark sc 25%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						534	0
FGD Refineries	12	661	7	26	106	522	7
1.0% new HC-PP	6	825	5			515	13
1.0% HC-Domestic	3	825	2			512	16
1.0% old HC-PP	90	825	74			421	90
FGD HF-Industry	62	873	54	195	623	359	145
1.0% new HFO-PP	2	1201	2			356	148
1.0% HFO-Domest.	10	1201	12			346	160
1.0% old HFO-PP	22	1201	26			324	186
FGD new HC-PP	16	1867	31	178	809	307	218
PROCESS-EM. 30%	0	2000	0			307	219
FGD old HC-PP	221	2438	539	3047	10622	86	759
0.3% MD-Domestic	4	3973	18			81	777
0.3% MD-Industry	3	3973	11			78	789
0.3% MD-Transp.	6	3973	24			72	814
PROCESS-EM. 60%	0	5000	1			71	815
FGD HC-Industry	6	6402	42	142	463	65	858
PROCESS-EM. 80%	0	8000	1			65	859
.15% MD-Transp.	4	8669	40			60	900
.15% MD-Domestic	3	8669	30			56	930
.15% MD-Industry	2	8669	19			54	950
FGD new HFO-PP	0	13725	7	60	284	54	957
FGD old HFO-PP	5	19069	97	767	2765	48	1055
RP Refineries	0	20086	7	60	106	48	1062
RP HF-Industry	1	25768	50	437	623	46	1113
RP HC-Industry	0	248189	51	317	463	46	1165
0.3% MD-Do							
0.3% MD-In							
0.3% MD-Tr							

Denmark sc 10%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						480	0
FGD Refineries	10	744	7	26	106	469	7
1.0% new HC-PP	3	825	3			465	11
1.0% HC-Domestic	1	825	1			464	12
1.0% old HC-PP	49	825	41			414	53
FGD HF-Industry	55	984	54	195	623	358	107
1.0% HFO-Domest.	19	1201	23			339	130
1.0% new HFO-PP	1	1201	2			337	133
1.0% old HFO-PP	18	1201	22			319	155
FGD new HC-PP	17	1989	33	178	809	302	189
PROCESS-EM. 30%	0	2000	0			301	190
FGD old HC-PP	223	2555	571	3047	10622	78	761
0.3% MD-Domestic	3	3973	13			75	774
0.3% MD-Industry	2	3973	8			72	782
0.3% MD-Transp.	4	3973	17			68	800
PROCESS-EM. 60%	0	5000	1			68	801
FGD HC-Industry	5	7309	42	142	463	62	843
PROCESS-EM. 80%	0	8000	1			62	845
.15% MD-Domestic	3	8669	30			58	875
.15% MD-Transp.	4	8669	40			54	916
.15% MD-Industry	2	8670	19			51	935
FGD new HFO-PP	0	14027	7	60	284	51	943
FGD old HFO-PP	5	19196	101	767	2765	46	1045
RP Refineries	0	23916	7	60	106	45	1053
RP HF-Industry	1	30346	52	437	623	43	1105
RP HC-Industry	0	284750	51	317	463	43	1157
0.3% MD-Do							
0.3% MD-In							
0.3% MD-Tr							

Denmark sc 1%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest --Mill.DM--	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						441	0
FGD Refineries	9	804	7	26	106	431	7
1.0% HC-Domestic	0	824	0			430	8
1.0% new HC-PP	1	825	1			428	10
1.0% old HC-PP	26	825	21			402	31
FGD HF-Industry	50	1066	54	195	623	351	85
1.0% old HFO-PP	16	1201	20			335	105
1.0% HFO-Domest.	17	1201	20			318	126
1.0% new HFO-PP	1	1201	2			316	128
PROCESS-EM. 30%	0	2000	0			316	129
FGD new HC-PP	17	2060	35	178	809	298	164
FGD old HC-PP	224	2623	589	3047	10622	74	753
0.3% MD-Domestic	2	3973	10			71	764
0.3% MD-Industry	1	3973	6			70	770
0.3% MD-Transp.	3	3973	13			66	784
PROCESS-EM. 60%	0	5000	1			66	785
FGD HC-Industry	5	7748	42	142	463	60	827
PROCESS-EM. 80%	0	8000	1			60	829
.15% MD-Domestic	3	8669	30			57	860
.15% MD-Industry	2	8669	19			54	879
.15% MD-Transp.	4	8669	40			50	919
FGD new HFO-PP	0	14195	7	60	284	49	927
FGD old HFO-PP	5	19266	103	767	2765	44	1031
RP Refineries	0	26688	8	60	106	44	1039
RP HF-Industry	1	33720	53	437	623	42	1093
RP HC-Industry	0	302476	51	317	463	42	1145
0.3% MD-Do							
0.3% MD-In							
0.3% MD-Tr							

Denmark sc -1%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest --Mill.DM--	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						438	0
FGD Refineries	9	819	7	26	106	428	7
1.0% HC-Domestic	0	824	0			428	8
1.0% old HC-PP	21	824	17			406	26
1.0% new HC-PP	1	825	1			405	27
FGD HF-Industry	55	976	54	195	623	349	81
1.0% new HFO-PP	1	1201	2			347	83
1.0% old HFO-PP	16	1201	19			331	103
1.0% HFO-Domest.	16	1201	20			314	123
PROCESS-EM. 30%	0	2000	0			314	123
FGD new HC-PP	17	2074	35	178	809	297	159
FGD old HC-PP	224	2637	593	3047	10622	72	752
0.3% MD-Domestic	2	3973	8			70	760
0.3% MD-Industry	1	3973	5			69	766
0.3% MD-Transp.	2	3973	11			66	777
PROCESS-EM. 60%	0	5000	1			66	778
PROCESS-EM. 80%	0	8000	1			65	780
FGD HC-Industry	5	8244	42	142	463	60	822
.15% MD-Domestic	3	8670	30			57	853
.15% MD-Industry	2	8670	19			54	872
.15% MD-Transp.	4	8670	40			50	913
FGD new HFO-PP	0	14232	7	60	284	49	921
FGD old HFO-PP	5	19282	104	767	2765	44	1025
RP Refineries	0	27383	8	60	106	44	1033
RP HF-Industry	1	30017	52	437	623	42	1086
RP HC-Industry	0	322490	51	317	463	42	1138
0.3% MD-Do							
0.3% MD-In							
0.3% MD-Tr							

Denmark sc -10%

_CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						398	0
FGD Refineries	8	897	7	26	106	390	7
FGD HF-Industry	50	1070	54	195	623	339	61
1.0% HFO-Domest.	14	1201	17			325	79
1.0% new HFO-PP	1	1201	1			323	80
1.0% old HFO-PP	14	1201	16			309	97
PROCESS-EM. 30%	0	2000	0			309	98
FGD new HC-PP	17	2158	36	178	809	292	135
FGD old HC-PP	223	2724	609	3047	10622	68	744
0.3% MD-Domestic	1	3973	5			67	750
0.3% MD-Transp.	1	3973	7			65	757
0.3% MD-Industry	0	3973	3			64	761
PROCESS-EM. 60%	0	5000	1			63	762
PROCESS-EM. 80%	0	8000	1			63	764
.15% MD-Domestic	3	8669	30			60	795
.15% MD-Transp.	4	8669	40			55	835
.15% MD-Industry	2	8670	19			53	855
FGD HC-Industry	4	8809	42	142	463	48	897
FGD new HFO-PP	0	14397	8	60	284	48	905
FGD old HFO-PP	5	19351	106	767	2765	42	1012
RP Refineries	0	30950	8	60	106	42	1020
RP HF-Industry	1	33852	53	437	623	40	1074
RP HC-Industry	0	345264	52	317	463	40	1126

0.3% MD-Do
0.3% MD-Tr
0.3% MD-In
PROCESS-EM
PROCESS-EM
.15% MD-Do

Denmark sc -25%

_CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						329	0
FGD Refineries	7	1063	7	26	106	321	7
1.0% HFO-Domest.	10	1201	13			310	20
1.0% HF-Industry	22	1201	27			288	48
1.0% old HFO-PP	10	1201	12			277	61
1.0% new HFO-PP	1	1201	1			276	62
FGD HF-Industry	14	1741	25	195	623	261	88
PROCESS-EM. 30%	0	2000	0			261	88
FGD new HC-PP	14	2564	36	178	809	246	125
FGD old HC-PP	187	3238	607	3047	10622	59	732
PROCESS-EM. 60%	0	5000	1			59	734
PROCESS-EM. 80%	0	8000	1			58	736
CM HC-Industry	2	10449	21	53	463	56	757
FGD HC-Industry	1	10836	20	142	463	54	778
FGD new HFO-PP	0	14653	8	60	284	54	786
FGD old HFO-PP	5	19458	110	767	2765	48	897
RP Refineries	0	38600	8	60	106	48	906
RP HF-Industry	1	48010	57	437	623	47	963
RP HC-Industry	0	418806	52	317	463	47	1015

1.0% new H
FGD HF-In
PROCESS-EM
FGD new H
FGD old H
PROCESS-EM
PROCESS-EM
CM HC-In
FGD HC-In
FGD new H

Denmark sc -50%

_CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						218	0
1.0% old HFO-PP	4	1201	5			213	5
1.0% HFO-Domest.	5	1201	6			208	11
1.0% HF-Industry	9	1201	11			199	23
1.0% new HFO-PP	0	1201	0			198	24
FGD Refineries	4	1569	7	26	106	193	31
PROCESS-EM. 30%	0	2000	0			193	32
FGD HF-Industry	15	2638	41	195	623	178	73
FGD new HC-PP	9	3840	36	178	809	168	109
FGD old HC-PP	124	4857	603	3047	10622	44	713
PROCESS-EM. 60%	0	5000	1			44	714
PROCESS-EM. 80%	0	8000	1			43	716
.15% MD-Domestic	1	8670	10			42	726
.15% MD-Industry	0	8670	6			41	733
.15% MD-Transp.	1	8670	13			40	746
CM HC-Industry	1	14964	20	53	463	39	767
FGD new HFO-PP	0	15052	9	60	284	38	776
FGD HC-Industry	1	16983	21	142	463	37	797
FGD old HFO-PP	5	19626	117	767	2765	31	915
RP Refineries	0	61900	9	60	106	31	924
RP HF-Industry	0	75706	60	437	623	30	984
RP HC-Industry	0	632078	52	317	463	30	1037
FGD new H							
FGD old H							
PROCESS-EM							
PROCESS-EM							
.15% MD-Do							
.15% MD-In							
.15% MD-Tr							

Denmark sc -75%

_CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						111	0
PROCESS-EM. 30%	0	2000	0			110	0
FGD Refineries	2	3064	7	26	106	108	8
FGD HF-Industry	12	4146	51	195	623	96	59
PROCESS-EM. 60%	0	5000	1			95	61
FGD new HC-PP	4	7487	36	178	809	90	97
PROCESS-EM. 80%	0	8000	1			90	99
FGD old HC-PP	63	9486	600	3047	10622	27	699
FGD new HFO-PP	0	17451	9	60	284	26	709
FGD old HFO-PP	5	22443	122	767	2765	21	832
CM HC-Industry	0	28508	19	53	463	20	851
FGD HC-Industry	0	35422	22	142	463	20	873
RP Refineries	0	130747	9	60	106	20	883
RP HF-Industry	0	160219	63	437	623	19	947
RP HC-Industry	01271893		52	317	463	19	1000

Cost Curves for Greece

Greece nominal

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						919	0
FGD new BC-PP	26	778	20	298	336	892	20
FGD Refineries	24	821	19	66	267	868	40
FGD new HFO-PP	10	845	8	47	195	858	48
FGD old BC-PP	541	964	522	7989	6936	317	571
FGD old HFO-PP	73	1055	77	439	1391	243	648
1.0% HFO-Domest.	7	1201	8			236	657
1.0% HF-Industry	24	1201	29			211	687
FGD HF-Industry	17	1877	32	229	730	194	720
FGD new HC-PP	0	1910	0	4	21	193	720
PROCESS-EM. 30%	4	2000	8			189	729
FGD old HC-PP	9	2398	23	114	433	179	753
FGD HC-Industry	22	2685	61	203	659	156	814
0.3% MD-Transp.	26	3973	104			130	919
0.3% MD-Domestic	12	3973	48			118	967
0.3% MD-Industry	2	3973	8			116	975
PROCESS-EM. 60%	4	5000	21			112	996
PROCESS-EM. 80%	2	8000	22			109	1019
.15% MD-Domestic	9	8669	78			100	1098
.15% MD-Transp.	7	8670	68			92	1166
.15% MD-Industry	0	8670	5			91	1172
RP Refineries	0	30604	23	151	267	90	1195
RP HF-Industry	1	55685	74	512	730	89	1270
RP HC-Industry	0	106630	76	452	659	88	1346
PROCESS-EM							
FGD old H							
FGD HC-In							
0.3% MD-Tr							
0.3% MD-Do							

Greece pf 75%

_CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						919	0
FGD new BC-PP	26	537	14	182	206	892	14
FGD new HFO-PP	10	543	5	27	111	882	19
FGD old BC-PP	541	651	352	4899	4253	341	372
FGD old HFO-PP	73	663	48	251	795	268	420
FGD Refineries	24	821	19	66	267	243	440
1.0% HFO-Domest.	7	1201	8			236	449
1.0% HF-Industry	24	1201	29			211	479
FGD new HC-PP	0	1208	0	2	12	211	479
FGD old HC-PP	9	1486	14	65	247	201	494
FGD HF-Industry	17	1877	32	229	730	183	527
PROCESS-EM. 30%	4	2000	8			179	535
FGD HC-Industry	22	2685	61	203	659	156	597
0.3% MD-Transp.	26	3973	104			130	701
0.3% MD-Domestic	12	3973	48			118	750
0.3% MD-Industry	2	3973	8			116	758
PROCESS-EM. 60%	4	5000	21			112	779
PROCESS-EM. 80%	2	8000	22			109	802
.15% MD-Domestic	9	8669	78			100	880
.15% MD-Transp.	7	8670	68			92	949
.15% MD-Industry	0	8670	5			91	955
RP Refineries	0	30604	23	151	267	90	978
RP HF-Industry	1	55685	74	512	730	89	1052
RP HC-Industry	0	106630	76	452	659	88	1129
FGD HF-In							
PROCESS-EM							
FGD HC-In							
0.3% MD-Tr							
0.3% MD-Do							

Greece pf 50%

_CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						919	0
FGD new BC-PP	26	570	14	198	224	892	14
FGD new HFO-PP	10	610	6	31	130	882	21
FGD old BC-PP	541	694	376	5326	4624	341	397
FGD old HFO-PP	73	750	54	293	927	268	452
FGD Refineries	24	821	19	66	267	243	472
1.0% HFO-Domest.	7	1201	8			236	480
1.0% HF-Industry	24	1201	29			211	510
FGD new HC-PP	0	1364	0	2	14	211	511
FGD old HC-PP	9	1689	16	76	288	201	528
FGD HF-Industry	17	1877	32	229	730	183	561
PROCESS-EM. 30%	4	2000	8			179	569
FGD HC-Industry	22	2685	61	203	659	156	630
0.3% MD-Transp.	26	3973	104			130	735
0.3% MD-Domestic	12	3973	48			118	783
0.3% MD-Industry	2	3973	8			116	792
PROCESS-EM. 60%	4	5000	21			112	813
PROCESS-EM. 80%	2	8000	22			109	835
.15% MD-Domestic	9	8669	78			100	914
.15% MD-Transp.	7	8670	68			92	982
.15% MD-Industry	0	8670	5			91	988
RP Refineries	0	30604	23	151	267	90	1011
RP HF-Industry	1	55685	74	512	730	89	1086
RP HC-Industry	0	106630	76	452	659	88	1163
FGD HF-In							
PROCESS-EM							
FGD HC-In							
0.3% MD-Tr							
0.3% MD-Do							

Greece pf 25%

_CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						919	0
FGD new BC-PP	26	653	17	238	269	892	17
FGD new HFO-PP	10	704	7	37	156	882	24
FGD old BC-PP	541	802	434	6391	5548	341	459
FGD Refineries	24	821	19	66	267	317	478
FGD old HFO-PP	73	872	63	351	1113	243	542
1.0% HFO-Domest.	7	1201	8			236	551
1.0% HF-Industry	24	1201	29			211	581
FGD new HC-PP	0	1582	0	3	17	211	582
FGD HF-Industry	17	1877	32	229	730	193	614
FGD old HC-PP	9	1972	19	91	346	183	634
PROCESS-EM. 30%	4	2000	8			179	643
FGD HC-Industry	22	2685	61	203	659	156	704
0.3% MD-Transp.	26	3973	104			130	808
0.3% MD-Domestic	12	3973	48			118	857
0.3% MD-Industry	2	3973	8			116	865
PROCESS-EM. 60%	4	5000	21			112	886
PROCESS-EM. 80%	2	8000	22			109	909
.15% MD-Domestic	9	8669	78			100	987
.15% MD-Transp.	7	8670	68			92	1056
.15% MD-Industry	0	8670	5			91	1062
RP Refineries	0	30604	23	151	267	90	1085
RP HF-Industry	1	55685	74	512	730	89	1159
RP HC-Industry	0	106630	76	452	659	88	1236

FGD old H
PROCESS-EM
FGD HC-In
0.3% MD-Tr
0.3% MD-Do

Greece pf 10%

_CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						919	0
FGD new BC-PP	26	721	18	271	306	892	18
FGD new HFO-PP	10	781	8	43	177	882	26
FGD Refineries	24	821	19	66	267	858	46
FGD old BC-PP	541	891	482	7263	6305	317	529
FGD old HFO-PP	73	972	71	399	1265	243	600
1.0% HFO-Domest.	7	1201	8			236	609
1.0% HF-Industry	24	1201	29			211	639
FGD new HC-PP	0	1761	0	3	19	211	639
FGD HF-Industry	17	1877	32	229	730	193	672
PROCESS-EM. 30%	4	2000	8			189	681
FGD old HC-PP	9	2204	22	104	393	179	703
FGD HC-Industry	22	2685	61	203	659	156	764
0.3% MD-Transp.	26	3973	104			130	869
0.3% MD-Domestic	12	3973	48			118	917
0.3% MD-Industry	2	3973	8			116	925
PROCESS-EM. 60%	4	5000	21			112	946
PROCESS-EM. 80%	2	8000	22			109	969
.15% MD-Domestic	9	8669	78			100	1048
.15% MD-Transp.	7	8670	68			92	1116
.15% MD-Industry	0	8670	5			91	1122
RP Refineries	0	30604	23	151	267	90	1145
RP HF-Industry	1	55685	74	512	730	89	1220
RP HC-Industry	0	106630	76	452	659	88	1296

PROCESS-EM
FGD old H
FGD HC-In
0.3% MD-Tr
0.3% MD-Do

Greece pf 1%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						919	0
FGD new BC-PP	26	772	20	295	333	892	20
FGD Refineries	24	821	19	66	267	868	40
FGD new HFO-PP	10	838	8	47	193	858	48
FGD old BC-PP	541	956	518	7910	6867	317	566
FGD old HFO-PP	73	1046	76	435	1377	243	643
1.0% HFO-Domest.	7	1201	8			236	652
1.0% HF-Industry	24	1201	29			211	681
FGD HF-Industry	17	1877	32	229	730	194	714
FGD new HC-PP	0	1894	0	4	21	193	715
PROCESS-EM. 30%	4	2000	8			189	724
FGD old HC-PP	9	2377	23	113	428	179	747
FGD HC-Industry	22	2685	61	203	659	156	809
0.3% MD-Transp.	26	3973	104			130	913
0.3% MD-Domestic	12	3973	48			118	962
0.3% MD-Industry	2	3973	8			116	970
PROCESS-EM. 60%	4	5000	21			112	991
PROCESS-EM. 80%	2	8000	22			109	1013
.15% MD-Domestic	9	8669	78			100	1092
.15% MD-Transp.	7	8670	68			92	1161
.15% MD-Industry	0	8670	5			91	1166
RP Refineries	0	30604	23	151	267	90	1190
RP HF-Industry	1	55685	74	512	730	89	1264
RP HC-Industry	0	106630	76	452	659	88	1341
PROCESS-EM							
FGD old H							
FGD HC-In							
0.3% MD-Tr							
0.3% MD-Do							

Greece pf -1%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						919	0
FGD new BC-PP	26	784	20	301	339	892	20
FGD Refineries	24	821	19	66	267	868	40
FGD new HFO-PP	10	852	8	47	197	858	49
FGD old BC-PP	541	972	526	8069	7005	317	576
FGD old HFO-PP	73	1064	77	444	1405	243	653
1.0% HFO-Domest.	7	1201	8			236	662
1.0% HF-Industry	24	1201	29			211	692
FGD HF-Industry	17	1877	32	229	730	194	725
FGD new HC-PP	0	1926	0	4	21	193	726
PROCESS-EM. 30%	4	2000	8			189	734
FGD old HC-PP	9	2419	24	115	437	179	758
FGD HC-Industry	22	2685	61	203	659	156	820
0.3% MD-Transp.	26	3973	104			130	924
0.3% MD-Domestic	12	3973	48			118	973
0.3% MD-Industry	2	3973	8			116	981
PROCESS-EM. 60%	4	5000	21			112	1002
PROCESS-EM. 80%	2	8000	22			109	1024
.15% MD-Domestic	9	8669	78			100	1103
.15% MD-Transp.	7	8670	68			92	1172
.15% MD-Industry	0	8670	5			91	1177
RP Refineries	0	30604	23	151	267	90	1201
RP HF-Industry	1	55685	74	512	730	89	1275
RP HC-Industry	0	106630	76	452	659	88	1352
PROCESS-EM							
FGD old H							
FGD HC-In							
0.3% MD-Tr							
0.3% MD-Do							

Greece pf -10%

_CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						919	0
FGD Refineries	24	821	19	66	267	895	19
FGD new BC-PP	26	848	22	331	373	868	42
FGD new HFO-PP	10	923	9	52	217	858	51
FGD old BC-PP	541	1054	571	8876	7706	317	622
FGD old HFO-PP	73	1157	84	488	1546	243	707
1.0% HFO-Domest.	7	1201	8			236	716
1.0% HF-Industry	24	1201	29			211	745
FGD HF-Industry	17	1877	32	229	730	194	778
PROCESS-EM. 30%	4	2000	8			190	787
FGD new HC-PP	0	2092	1	4	23	189	788
FGD old HC-PP	9	2634	26	127	481	179	814
FGD HC-Industry	22	2685	61	203	659	156	875
0.3% MD-Transp.	26	3973	104			130	980
0.3% MD-Domestic	12	3973	48			118	1028
0.3% MD-Industry	2	3973	8			116	1037
PROCESS-EM. 60%	4	5000	21			112	1058
PROCESS-EM. 80%	2	8000	22			109	1080
.15% MD-Domestic	9	8669	78			100	1159
.15% MD-Transp.	7	8670	68			92	1228
.15% MD-Industry	0	8670	5			91	1233
RP Refineries	0	30604	23	151	267	90	1256
RP HF-Industry	1	55685	74	512	730	89	1331
RP HC-Industry	0	106630	76	452	659	88	1408
FGD new H							
FGD old H							
FGD HC-In							
0.3% MD-Tr							
0.3% MD-Do							

Greece pf -25%

_CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						919	0
FGD Refineries	24	821	19	66	267	895	19
FGD new BC-PP	26	986	25	397	448	868	45
FGD new HFO-PP	10	1080	11	63	260	858	56
1.0% HFO-Domest.	7	1201	8			851	65
1.0% HF-Industry	24	1201	29			826	95
1.0% old HFO-PP	54	1201	66			771	161
FGD old BC-PP	541	1234	668	10652	9248	230	830
FGD old HFO-PP	18	1844	33	586	1855	211	863
FGD HF-Industry	17	1877	32	229	730	194	896
PROCESS-EM. 30%	4	2000	8			190	904
FGD new HC-PP	0	2456	1	5	28	189	906
FGD HC-Industry	22	2685	61	203	659	166	967
FGD old HC-PP	9	3107	31	152	577	156	998
0.3% MD-Transp.	26	3973	104			130	1103
0.3% MD-Domestic	12	3973	48			118	1151
0.3% MD-Industry	2	3973	8			116	1159
PROCESS-EM. 60%	4	5000	21			112	1180
PROCESS-EM. 80%	2	8000	22			109	1203
.15% MD-Domestic	9	8669	78			100	1282
.15% MD-Transp.	7	8670	68			92	1350
.15% MD-Industry	0	8670	5			91	1356
RP Refineries	0	30604	23	151	267	90	1379
RP HF-Industry	1	55685	74	512	730	89	1454
RP HC-Industry	0	106630	76	452	659	88	1530
FGD new H							
FGD HC-In							
FGD old H							
0.3% MD-Tr							

Greece pf -50%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						919	0
FGD Refineries	24	821	19	66	267	895	19
1.0% HFO-Domest.	7	1201	8			887	28
1.0% HF-Industry	24	1201	29			863	58
1.0% new HFO-PP	7	1201	9			855	67
1.0% old HFO-PP	54	1201	66			800	133
FGD new BC-PP	26	1402	36	596	673	774	170
FGD old BC-PP	541	1775	961	15979	13872	232	1131
FGD HF-Industry	17	1877	32	229	730	215	1164
PROCESS-EM. 30%	4	2000	8			210	1173
FGD new HFO-PP	2	2611	6	94	390	208	1179
FGD HC-Industry	22	2685	61	203	659	185	1241
FGD new HC-PP	0	3549	1	8	42	184	1242
0.3% MD-Domestic	12	3973	48			172	1291
0.3% MD-Industry	2	3973	8			170	1299
0.3% MD-Transp.	26	3973	104			144	1404
FGD old HFO-PP	18	4304	78	879	2783	126	1482
FGD old HC-PP	9	4524	45	229	866	116	1527
PROCESS-EM. 60%	4	5000	21			112	1548
PROCESS-EM. 80%	2	8000	22			109	1570
.15% MD-Domestic	9	8669	78			100	1649
.15% MD-Transp.	7	8670	68			92	1718
.15% MD-Industry	0	8670	5			91	1723
RP Refineries	0	30604	23	151	267	90	1747
RP HF-Industry	1	55685	74	512	730	89	1821
RP HC-Industry	0	106630	76	452	659	88	1898
FGD new H							
0.3% MD-Do							
0.3% MD-In							

Greece pf -75%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						919	0
FGD Refineries	24	821	19	66	267	895	19
1.0% HFO-Domest.	7	1201	8			887	28
1.0% HF-Industry	24	1201	29			863	58
1.0% new HFO-PP	7	1201	9			855	67
1.0% old HFO-PP	54	1201	66			800	133
FGD HF-Industry	17	1877	32	229	730	782	166
PROCESS-EM. 30%	4	2000	8			778	174
FGD new BC-PP	26	2651	69	1192	1346	752	244
FGD HC-Industry	22	2685	61	203	659	729	305
FGD old BC-PP	541	3396	1839	31958	27744	188	2145
0.3% MD-Domestic	12	3973	48			175	2193
0.3% MD-Industry	2	3973	8			173	2201
0.3% MD-Transp.	26	3973	104			147	2306
PROCESS-EM. 60%	4	5000	21			143	2327
FGD new HC-PP	0	6826	3	17	85	142	2330
PROCESS-EM. 80%	2	8000	22			139	2353
FGD new HFO-PP	2	8300	21	189	781	137	2374
.15% MD-Domestic	9	8669	78			128	2453
.15% MD-Transp.	7	8670	68			120	2521
.15% MD-Industry	0	8670	5			119	2527
FGD old HC-PP	9	8777	87	458	1732	109	2615
FGD old HFO-PP	18	11686	211	1759	5566	91	2826
RP Refineries	0	30604	23	151	267	90	2850
RP HF-Industry	1	55685	74	512	730	89	2924
RP HC-Industry	0	106630	76	452	659	88	3001
0.3% MD-In							
0.3% MD-Tr							
PROCESS-EM							

Greece sc 75%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill	invest .DM--	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						919	0
FGD new BC-PP	45	469	21	298	336	873	21
FGD Refineries	42	493	20	66	267	831	42
FGD new HFO-PP	17	507	9	47	195	813	51
FGD old BC-PP	947	575	545	7989	6936	-134	597
FGD old HFO-PP	127	627	80	439	1391	-262	677
1.0% HC-Industry	18	847	15			-280	692
1.0% new HC-PP	0	847	0			-280	693
1.0% old HC-PP	7	847	6			-288	699
FGD HF-Industry	74	869	64	229	730	-363	764
1.0% HFO-Domest.	14	1201	17			-378	782
FGD new HC-PP	0	1336	0	4	21	-378	783
FGD old HC-PP	9	1844	17	114	433	-388	800
PROCESS-EM. 30%	4	2000	8			-392	809
FGD HC-Industry	21	2144	46	203	659	-414	856
0.3% MD-Transp.	57	3973	230			-472	1086
0.3% MD-Domestic	35	3973	139			-507	1226
0.3% MD-Industry	4	3973	18			-512	1244
PROCESS-EM. 60%	4	5000	21			-516	1265
PROCESS-EM. 80%	2	8000	22			-519	1288
.15% MD-Transp.	7	8669	68			-526	1356
.15% MD-Domestic	9	8669	78			-536	1435
.15% MD-Industry	0	8669	5			-536	1441
RP Refineries	1	14154	18	151	267	-537	1460
RP HF-Industry	2	28458	66	512	730	-540	1526
RP HC-Industry	1	57615	72	452	659	-541	1599
FGD old H							
PROCESS-EM							
FGD HC-In							

Greece sc 50%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill	invest .DM--	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						919	0
FGD new BC-PP	39	538	21	298	336	879	21
FGD Refineries	36	566	20	66	267	843	41
FGD new HFO-PP	15	582	8	47	195	828	50
FGD old BC-PP	812	662	538	7989	6936	15	588
FGD old HFO-PP	109	722	79	439	1391	-93	667
1.0% new HC-PP	0	847	0			-93	668
1.0% HC-Industry	12	847	10			-105	678
1.0% old HC-PP	5	847	4			-111	682
FGD HF-Industry	63	1006	64	229	730	-174	746
1.0% HFO-Domest.	12	1201	14			-187	761
FGD new HC-PP	0	1533	0	4	21	-187	762
PROCESS-EM. 30%	4	2000	8			-191	770
FGD old HC-PP	9	2034	19	114	433	-201	790
FGD HC-Industry	22	2329	51	203	659	-223	842
0.3% MD-Domestic	27	3973	108			-250	950
0.3% MD-Industry	3	3973	15			-254	965
0.3% MD-Transp.	47	3973	188			-302	1154
PROCESS-EM. 60%	4	5000	21			-306	1175
PROCESS-EM. 80%	2	8000	22			-309	1197
.15% MD-Transp.	7	8669	68			-317	1266
.15% MD-Industry	0	8669	5			-317	1271
.15% MD-Domestic	9	8670	78			-326	1350
RP Refineries	1	17824	20	151	267	-328	1371
RP HF-Industry	2	34544	69	512	730	-330	1440
RP HC-Industry	1	68507	73	452	659	-331	1514
PROCESS-EM							
FGD old H							
FGD HC-In							

Greece sc 25%

_CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						1146	0
FGD new BC-PP	32	634	20	298	336	1113	20
FGD Refineries	30	667	20	66	267	1083	40
FGD new HFO-PP	12	687	8	47	195	1070	49
FGD old BC-PP	676	783	530	7989	6936	393	580
1.0% old HC-PP	2	847	2			390	582
1.0% new HC-PP	0	847	0			390	582
1.0% HC-Industry	6	847	5			384	587
FGD old HFO-PP	91	855	78	439	1391	293	665
FGD HF-Industry	53	1194	63	229	730	240	729
1.0% HFO-Domest.	9	1201	11			230	740
FGD new HC-PP	0	1724	0	4	21	229	741
PROCESS-EM. 30%	4	2000	8			225	750
FGD old HC-PP	9	2218	21	114	433	215	771
FGD HC-Industry	22	2510	56	203	659	193	828
0.3% MD-Industry	2	3973	11			190	840
0.3% MD-Transp.	36	3973	146			153	986
0.3% MD-Domestic	20	3973	79			133	1066
PROCESS-EM. 60%	4	5000	21			129	1087
PROCESS-EM. 80%	2	8000	22			126	1109
.15% MD-Transp.	7	8669	68			118	1178
.15% MD-Industry	0	8669	5			117	1183
.15% MD-Domestic	9	8669	78			108	1262
RP Refineries	0	22901	21	151	267	107	1284
RP HF-Industry	1	42911	71	512	730	106	1356
RP HC-Industry	0	83756	75	452	659	105	1431
PROCESS-EM							
FGD old H							
FGD HC-In							

Greece sc 10%

_CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						1009	0
FGD new BC-PP	28	713	20	298	336	980	20
FGD Refineries	26	751	19	66	267	954	40
FGD new HFO-PP	11	773	8	47	195	943	49
1.0% new HC-PP	0	847	0			943	49
1.0% HC-Industry	2	847	2			940	51
1.0% old HC-PP	1	847	0			939	52
FGD old BC-PP	595	882	525	7989	6936	343	577
FGD old HFO-PP	80	964	77	439	1391	263	655
1.0% HF-Industry	29	1201	35			234	690
1.0% HFO-Domest.	8	1201	9			225	700
FGD HF-Industry	17	1600	27	229	730	208	728
FGD new HC-PP	0	1836	0	4	21	208	729
PROCESS-EM. 30%	4	2000	8			203	737
FGD old HC-PP	9	2326	23	114	433	193	760
FGD HC-Industry	22	2616	59	203	659	171	820
0.3% MD-Domestic	15	3973	60			156	880
0.3% MD-Industry	2	3973	9			153	890
0.3% MD-Transp.	30	3973	121			123	1011
PROCESS-EM. 60%	4	5000	21			118	1032
PROCESS-EM. 80%	2	8000	22			116	1055
.15% MD-Transp.	7	8669	68			108	1123
.15% MD-Industry	0	8669	5			107	1129
.15% MD-Domestic	9	8669	78			98	1208
RP Refineries	0	27118	22	151	267	97	1230
RP HF-Industry	1	49827	73	512	730	96	1304
RP HC-Industry	0	96233	76	452	659	95	1380
PROCESS-EM							
FGD old H							

Greece sc 1%

_CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill	invest .DM--	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						932	0
FGD new BC-PP	26	766	20	298	336	906	20
FGD Refineries	24	812	19	66	267	881	40
FGD new HFO-PP	10	836	8	47	195	871	48
1.0% new HC-PP	0	847	0			871	48
1.0% old HC-PP	0	847	0			871	49
1.0% HC-Industry	0	847	0			871	49
FGD old BC-PP	550	949	523	7989	6936	320	572
FGD old HFO-PP	73	1044	77	439	1391	246	649
1.0% HF-Industry	25	1201	30			221	679
1.0% HFO-Domest.	7	1201	8			214	688
FGD HF-Industry	17	1853	32	229	730	196	721
FGD new HC-PP	0	1902	0	4	21	196	722
PROCESS-EM. 30%	4	2000	8			191	730
FGD old HC-PP	9	2391	23	114	433	181	754
FGD HC-Industry	22	2678	61	203	659	159	815
0.3% MD-Transp.	26	3973	106			132	922
0.3% MD-Domestic	12	3973	50			119	972
0.3% MD-Industry	2	3973	8			117	981
PROCESS-EM. 60%	4	5000	21			113	1002
PROCESS-EM. 80%	2	8000	22			110	1024
.15% MD-Domestic	9	8670	78			101	1103
.15% MD-Transp.	7	8670	68			93	1172
.15% MD-Industry	0	8670	5			92	1177
RP Refineries	0	30171	23	151	267	91	1200
RP HF-Industry	1	55129	74	512	730	90	1275
RP HC-Industry	0	105497	76	452	659	89	1352
PROCESS-EM							
FGD old H							

Greece sc -1%

_CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill	invest .DM--	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						905	0
FGD new BC-PP	25	790	20	298	336	879	20
FGD Refineries	23	827	19	66	267	856	40
FGD new HFO-PP	10	852	8	47	195	845	48
FGD old BC-PP	532	980	522	7989	6936	313	570
FGD old HFO-PP	72	1064	77	439	1391	240	647
1.0% HF-Industry	24	1201	29			216	677
1.0% HFO-Domest.	7	1201	8			209	685
FGD HF-Industry	17	1901	33	229	730	191	719
FGD new HC-PP	0	1929	0	4	21	191	720
PROCESS-EM. 30%	4	2000	8			187	728
FGD old HC-PP	9	2421	23	114	433	177	752
FGD HC-Industry	22	2712	61	203	659	154	813
0.3% MD-Transp.	25	3973	102			128	916
0.3% MD-Domestic	11	3973	45			117	962
0.3% MD-Industry	2	3973	8			115	970
PROCESS-EM. 60%	4	5000	21			110	991
PROCESS-EM. 80%	2	8000	22			108	1013
.15% MD-Domestic	9	8669	78			99	1092
.15% MD-Transp.	7	8670	68			91	1161
.15% MD-Industry	0	8670	5			90	1166
RP Refineries	0	30935	23	151	267	89	1190
RP HF-Industry	1	56251	74	512	730	88	1264
RP HC-Industry	0	107785	76	452	659	87	1341
PROCESS-EM							
FGD old H							
FGD HC-In							
0.3% MD-Tr							
0.3% MD-Do							

Greece sc -10%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						828	0
FGD new BC-PP	23	858	20	298	336	804	20
FGD Refineries	21	905	19	66	267	783	39
FGD new HFO-PP	9	933	8	47	195	774	48
FGD old BC-PP	487	1065	519	7989	6936	286	567
FGD old HFO-PP	65	1166	76	439	1391	220	644
1.0% HFO-Domest.	6	1201	7			214	652
1.0% HF-Industry	20	1201	24			194	676
PROCESS-EM. 30%	4	2000	8			190	684
FGD new HC-PP	0	2116	0	4	21	189	685
FGD HF-Industry	17	2146	38	229	730	171	724
FGD old HC-PP	8	2658	23	114	433	162	747
FGD HC-Industry	20	2977	61	203	659	142	809
0.3% MD-Industry	1	3973	7			140	816
0.3% MD-Transp.	22	3973	87			118	904
0.3% MD-Domestic	9	3973	36			109	940
PROCESS-EM. 60%	4	5000	21			105	961
PROCESS-EM. 80%	2	8000	22			102	983
.15% MD-Industry	0	8669	5			101	989
.15% MD-Transp.	7	8669	68			93	1057
.15% MD-Domestic	9	8670	78			84	1136
RP Refineries	0	34864	23	151	267	84	1160
RP HF-Industry	1	62871	75	512	730	82	1236
RP HC-Industry	0	119337	77	452	659	82	1313
FGD HF-In							
FGD old H							
FGD HC-In							
0.3% MD-In							
0.3% MD-Tr							

Greece sc -25%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						693	0
FGD new BC-PP	19	1019	20	298	336	673	20
FGD Refineries	18	1073	19	66	267	655	39
FGD new HFO-PP	7	1106	8	47	195	648	48
1.0% HFO-Domest.	4	1201	5			643	53
1.0% old HFO-PP	35	1201	43			607	96
1.0% HF-Industry	13	1201	16			593	113
FGD old BC-PP	406	1267	514	7989	6936	187	628
FGD old HFO-PP	19	1731	33	439	1391	168	661
PROCESS-EM. 30%	4	2000	8			164	669
FGD HF-Industry	18	2521	45	229	730	146	715
FGD new HC-PP	0	2527	0	4	21	145	716
FGD old HC-PP	7	3178	23	114	433	138	739
FGD HC-Industry	17	3561	60	203	659	121	800
0.3% MD-Transp.	15	3973	62			105	863
0.3% MD-Domestic	4	3973	19			100	882
0.3% MD-Industry	1	3973	5			99	887
PROCESS-EM. 60%	4	5000	21			94	908
PROCESS-EM. 80%	2	8000	22			92	931
.15% MD-Domestic	9	8669	78			83	1010
.15% MD-Industry	0	8669	5			82	1015
.15% MD-Transp.	7	8669	68			74	1084
RP Refineries	0	43287	24	151	267	73	1109
RP HF-Industry	1	76577	77	512	730	72	1186
RP HC-Industry	0	144752	78	452	659	72	1264
FGD new H							
FGD old H							
FGD HC-In							
0.3% MD-Tr							

Greece sc -50%

_CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						466	0
1.0% HFO-Domest.	2	1201	2			464	2
1.0% new HFO-PP	2	1201	2			462	5
1.0% old HFO-PP	16	1201	19			445	25
1.0% HF-Industry	2	1201	3			443	28
FGD new BC-PP	13	1499	19	298	336	429	47
FGD Refineries	12	1584	19	66	267	417	67
FGD old BC-PP	270	1872	506	7989	6936	147	573
FGD new HFO-PP	2	1988	5	47	195	144	579
PROCESS-EM. 30%	4	2000	8			140	587
FGD old HFO-PP	20	2754	55	439	1391	120	643
FGD HF-Industry	18	3138	58	229	730	101	701
FGD new HC-PP	0	3763	0	4	21	101	702
0.3% MD-Industry	0	3973	1			100	704
0.3% MD-Transp.	5	3973	20			95	725
FGD old HC-PP	4	4738	23	114	433	90	748
PROCESS-EM. 60%	4	5000	21			86	769
FGD HC-Industry	11	5314	60	203	659	74	830
PROCESS-EM. 80%	2	8000	22			72	852
.15% MD-Domestic	6	8669	52			66	905
.15% MD-Industry	0	8670	5			65	911
.15% MD-Transp.	7	8670	68			57	979
RP Refineries	0	68945	26	151	267	57	1005
RP HF-Industry	0	119107	79	512	730	56	1085
RP HC-Industry	0	220997	79	452	659	56	1165
FGD HF-In							
FGD new H							
0.3% MD-In							
0.3% MD-Tr							

Greece sc -75%

_CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						240	0
PROCESS-EM. 30%	4	2000	8			236	8
FGD new BC-PP	6	2942	19	298	336	230	27
FGD Refineries	6	3094	18	66	267	224	46
FGD new HFO-PP	2	3191	8	47	195	221	54
FGD old BC-PP	135	3686	499	7989	6936	86	553
FGD old HFO-PP	18	4027	73	439	1391	67	627
PROCESS-EM. 60%	4	5000	21			63	648
FGD HF-Industry	10	5700	60	229	730	52	709
FGD new HC-PP	0	7468	0	4	21	52	710
PROCESS-EM. 80%	2	8000	22			49	733
.15% MD-Industry	0	8670	1			49	734
.15% MD-Transp.	2	8670	22			47	757
FGD old HC-PP	2	9420	23	114	433	44	781
CM HC-Industry	3	10479	31	75	659	41	812
FGD HC-Industry	2	10672	28	203	659	38	841
RP Refineries	0	144756	27	151	267	38	869
RP HF-Industry	0	243726	82	512	730	38	951
RP HC-Industry	0	449731	80	452	659	38	1032
FGD old B							
FGD old H							
PROCESS-EM							
FGD HF-In							
FGD new H							
PROCESS-EM							
.15% MD-In							
.15% MD-Tr							
FGD old H							
CM HC-In							

Cost Curves for Poland

Poland - nominal

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SCENARIO: Official Energy Pathway (OEP)

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CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs	a a a
Unabated SO2						4144	0	
1.0% new HC-PP	17	533	9			4127	9	
1.0% old HC-PP	192	533	102			3934	111	
FGD new HFO-PP	8	908	7	42	203	3925	119	
FGD new HC-PP	162	1031	167	811	3985	3763	287	
FGD Refineries	50	1092	55	194	784	3713	342	
FGD old HFO-PP	172	1134	195	1090	4009	3540	537	
1.0% HFO-Domest.	13	1201	16			3527	554	
1.0% HF-Industry	16	1201	19			3510	574	
FGD old HC-PP	1819	1308	2379	11836	44723	1691	2954	
FGD new BC-PP	59	1370	81	1288	1433	1631	3035	
FGD HF-Industry	9	1497	14	128	409	1622	3049	
FGD old BC-PP	487	1734	845	13791	11800	1134	3895	
PROCESS-EM. 30%	28	2000	57			1105	3953	
FGD HC-Industry	48	2128	102	346	1122	1057	4055	
FGD Cokeplants	111	2445	271	857	3546	946	4326	
FGD DC-Industry	70	3068	215	736	2388	876	4542	
0.3% MD-Transp.	43	3973	172			833	4715	
0.3% MD-Domestic	6	3973	24			826	4739	
PROCESS-EM. 60%	28	5000	144			798	4883	
PROCESS-EM. 80%	19	8000	153			778	5037	
.15% MD-Transp.	21	8669	187			757	5225	
.15% MD-Domestic	3	8670	26			754	5252	
RP Refineries	1	37315	59	445	784	752	5311	
RP HF-Industry	0	40971	34	287	409	751	5345	
RP HC-Industry	1	71642	108	769	1122	750	5454	
RP DC-Industry	2	107684	239	1637	2388	747	5693	
PROCESS-EM								
FGD HC-In								

Poland pf 75%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						4144	0
1.0% new HC-PP	17	533	9			4127	9
1.0% old HC-PP	192	533	102			3934	111
FGD new HFO-PP	8	582	5	24	116	3925	117
FGD new HC-PP	162	633	102	463	2277	3763	219
FGD old HFO-PP	172	711	122	623	2290	3591	342
FGD old HC-PP	1819	791	1439	6763	25556	1771	1782
FGD new BC-PP	59	847	50	736	819	1712	1832
FGD old BC-PP	487	1054	514	7880	6743	1225	2346
FGD Refineries	50	1092	55	194	784	1174	2401
1.0% HFO-Domest.	13	1201	16			1161	2418
1.0% HF-Industry	16	1201	19			1144	2438
FGD HF-Industry	9	1497	14	128	409	1134	2452
PROCESS-EM. 30%	28	2000	57			1105	2510
FGD HC-Industry	48	2128	102	346	1122	1057	2612
FGD Cokeplants	111	2445	271	857	3546	946	2884
FGD DC-Industry	70	3068	215	736	2388	876	3100
0.3% MD-Transp.	43	3973	172			833	3272
0.3% MD-Domestic	6	3973	24			826	3297
PROCESS-EM. 60%	28	5000	144			798	3441
PROCESS-EM. 80%	19	8000	153			778	3594
.15% MD-Transp.	21	8669	187			757	3782
.15% MD-Domestic	3	8670	26			754	3809
RP Refineries	1	37315	59	445	784	752	3868
RP HF-Industry	0	40971	34	287	409	751	3903
RP HC-Industry	1	71642	108	769	1122	750	4011
RP DC-Industry	2	107684	239	1637	2388	747	4251
PROCESS-EM							
FGD HC-In							

Poland pf 50%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						4144	0
1.0% new HC-PP	17	533	9			4127	9
1.0% old HC-PP	192	533	102			3934	111
FGD new HFO-PP	8	654	5	28	135	3925	117
FGD new HC-PP	162	721	117	540	2656	3763	234
FGD old HFO-PP	172	805	139	727	2672	3591	373
FGD old HC-PP	1819	906	1648	7891	29815	1771	2022
FGD new BC-PP	59	963	57	858	955	1712	2079
FGD Refineries	50	1092	55	194	784	1662	2134
1.0% HFO-Domest.	13	1201	16			1648	2151
1.0% HF-Industry	16	1201	19			1631	2171
FGD old BC-PP	487	1205	587	9194	7867	1144	2758
FGD HF-Industry	9	1497	14	128	409	1134	2773
PROCESS-EM. 30%	28	2000	57			1105	2831
FGD HC-Industry	48	2128	102	346	1122	1057	2933
FGD Cokeplants	111	2445	271	857	3546	946	3204
FGD DC-Industry	70	3068	215	736	2388	876	3420
0.3% MD-Transp.	43	3973	172			833	3593
0.3% MD-Domestic	6	3973	24			826	3617
PROCESS-EM. 60%	28	5000	144			798	3761
PROCESS-EM. 80%	19	8000	153			778	3915
.15% MD-Transp.	21	8669	187			757	4103
.15% MD-Domestic	3	8670	26			754	4130
RP Refineries	1	37315	59	445	784	752	4189
RP HF-Industry	0	40971	34	287	409	751	4223
RP HC-Industry	1	71642	108	769	1122	750	4332
RP DC-Industry	2	107684	239	1637	2388	747	4571
PROCESS-EM							
FGD HC-In							

Poland pf 25%

_CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						4144	0
1.0% new HC-PP	17	533	9			4127	9
1.0% old HC-PP	192	533	102			3934	111
FGD new HFO-PP	8	756	6	34	162	3925	118
FGD new HC-PP	162	845	137	649	3188	3763	255
FGD old HFO-PP	172	937	161	872	3207	3591	417
FGD old HC-PP	1819	1066	1941	9469	35778	1771	2358
FGD Refineries	50	1092	55	194	784	1721	2413
FGD new BC-PP	59	1126	66	1030	1146	1662	2480
1.0% HFO-Domest.	13	1201	16			1648	2496
1.0% HF-Industry	16	1201	19			1631	2516
FGD old BC-PP	487	1417	690	11032	9440	1144	3207
FGD HF-Industry	9	1497	14	128	409	1134	3222
PROCESS-EM. 30%	28	2000	57			1105	3279
FGD HC-Industry	48	2128	102	346	1122	1057	3382
FGD Cokeplants	111	2445	271	857	3546	946	3653
FGD DC-Industry	70	3068	215	736	2388	876	3869
0.3% MD-Transp.	43	3973	172			833	4041
0.3% MD-Domestic	6	3973	24			826	4066
PROCESS-EM. 60%	28	5000	144			798	4210
PROCESS-EM. 80%	19	8000	153			778	4364
.15% MD-Transp.	21	8669	187			757	4552
.15% MD-Domestic	3	8670	26			754	4579
RP Refineries	1	37315	59	445	784	752	4638
RP HF-Industry	0	40971	34	287	409	751	4672
RP HC-Industry	1	71642	108	769	1122	750	4781
RP DC-Industry	2	107684	239	1637	2388	747	5020
PROCESS-EM							
FGD HC-In							

Poland pf 10%

_CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						4144	0
1.0% new HC-PP	17	533	9			4127	9
1.0% old HC-PP	192	533	102			3934	111
FGD new HFO-PP	8	839	7	38	184	3925	119
FGD new HC-PP	162	947	153	737	3622	3763	272
FGD old HFO-PP	172	1044	180	991	3644	3591	453
FGD Refineries	50	1092	55	194	784	3540	508
FGD old HC-PP	1819	1198	2180	10760	40656	1721	2688
1.0% HFO-Domest.	13	1201	16			1707	2705
1.0% HF-Industry	16	1201	19			1691	2725
FGD new BC-PP	59	1259	74	1171	1302	1631	2799
FGD HF-Industry	9	1497	14	128	409	1622	2814
FGD old BC-PP	487	1589	775	12537	10727	1134	3589
PROCESS-EM. 30%	28	2000	57			1105	3646
FGD HC-Industry	48	2128	102	346	1122	1057	3749
FGD Cokeplants	111	2445	271	857	3546	946	4020
FGD DC-Industry	70	3068	215	736	2388	876	4236
0.3% MD-Transp.	43	3973	172			833	4409
0.3% MD-Domestic	6	3973	24			826	4433
PROCESS-EM. 60%	28	5000	144			798	4577
PROCESS-EM. 80%	19	8000	153			778	4731
.15% MD-Transp.	21	8669	187			757	4919
.15% MD-Domestic	3	8670	26			754	4946
RP Refineries	1	37315	59	445	784	752	5005
RP HF-Industry	0	40971	34	287	409	751	5039
RP HC-Industry	1	71642	108	769	1122	750	5148
RP DC-Industry	2	107684	239	1637	2388	747	5387
PROCESS-EM							
FGD HC-In							

Poland pf 1%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						4144	0
1.0% new HC-PP	17	533	9			4127	9
1.0% old HC-PP	192	533	102			3934	111
FGD new HFO-PP	8	900	7	42	201	3925	119
FGD new HC-PP	162	1022	165	803	3945	3763	285
FGD Refineries	50	1092	55	194	784	3713	340
FGD old HFO-PP	172	1124	194	1079	3969	3540	534
1.0% HFO-Domest.	13	1201	16			3527	551
1.0% HF-Industry	16	1201	19			3510	571
FGD old HC-PP	1819	1296	2358	11718	44277	1691	2929
FGD new BC-PP	59	1358	80	1275	1418	1631	3009
FGD HF-Industry	9	1497	14	128	409	1622	3024
FGD old BC-PP	487	1718	837	13654	11683	1134	3861
PROCESS-EM. 30%	28	2000	57			1105	3919
FGD HC-Industry	48	2128	102	346	1122	1057	4021
FGD Cokeplants	111	2445	271	857	3546	946	4293
FGD DC-Industry	70	3068	215	736	2388	876	4509
0.3% MD-Transp.	43	3973	172			833	4681
0.3% MD-Domestic	6	3973	24			826	4706
PROCESS-EM. 60%	28	5000	144			798	4850
PROCESS-EM. 80%	19	8000	153			778	5003
.15% MD-Transp.	21	8669	187			757	5191
.15% MD-Domestic	3	8670	26			754	5218
RP Refineries	1	37315	59	445	784	752	5277
RP HF-Industry	0	40971	34	287	409	751	5312
RP HC-Industry	1	71642	108	769	1122	750	5420
RP DC-Industry	2	107684	239	1637	2388	747	5660
PROCESS-EM							
FGD HC-In							

Poland pf -1%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						4144	0
1.0% new HC-PP	17	533	9			4127	9
1.0% old HC-PP	192	533	102			3934	111
FGD new HFO-PP	8	916	8	43	205	3925	119
FGD new HC-PP	162	1041	168	819	4025	3763	288
FGD Refineries	50	1092	55	194	784	3713	343
FGD old HFO-PP	172	1144	197	1101	4050	3540	541
1.0% HFO-Domest.	13	1201	16			3527	557
1.0% HF-Industry	16	1201	19			3510	577
FGD old HC-PP	1819	1320	2402	11957	45178	1691	2979
FGD new BC-PP	59	1382	81	1301	1447	1631	3061
FGD HF-Industry	9	1497	14	128	409	1622	3076
FGD old BC-PP	487	1750	853	13931	11920	1134	3929
PROCESS-EM. 30%	28	2000	57			1105	3987
FGD HC-Industry	48	2128	102	346	1122	1057	4089
FGD Cokeplants	111	2445	271	857	3546	946	4361
FGD DC-Industry	70	3068	215	736	2388	876	4577
0.3% MD-Transp.	43	3973	172			833	4749
0.3% MD-Domestic	6	3973	24			826	4773
PROCESS-EM. 60%	28	5000	144			798	4917
PROCESS-EM. 80%	19	8000	153			778	5071
.15% MD-Transp.	21	8669	187			757	5259
.15% MD-Domestic	3	8670	26			754	5286
RP Refineries	1	37315	59	445	784	752	5345
RP HF-Industry	0	40971	34	287	409	751	5379
RP HC-Industry	1	71642	108	769	1122	750	5488
RP DC-Industry	2	107684	239	1637	2388	747	5727
PROCESS-EM							
FGD HC-In							

Poland pf -10%

_CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						4144	0
1.0% new HC-PP	17	533	9			4127	9
1.0% old HC-PP	192	533	102			3934	111
FGD new HFO-PP	8	993	8	47	226	3925	120
FGD Refineries	50	1092	55	194	784	3875	175
FGD new HC-PP	162	1134	184	901	4428	3713	359
1.0% HFO-Domest.	13	1201	16			3699	376
1.0% HF-Industry	16	1201	19			3683	396
1.0% old HFO-PP	100	1201	121			3582	517
FGD old HFO-PP	71	1304	93	1212	4454	3510	610
FGD old HC-PP	1819	1442	2623	13152	49695	1691	3234
FGD HF-Industry	9	1497	14	128	409	1681	3249
FGD new BC-PP	59	1505	89	1431	1592	1622	3338
FGD old BC-PP	487	1910	931	15323	13111	1134	4269
PROCESS-EM. 30%	28	2000	57			1105	4327
FGD HC-Industry	48	2128	102	346	1122	1057	4429
FGD Cokeplants	111	2445	271	857	3546	946	4701
FGD DC-Industry	70	3068	215	736	2388	876	4916
0.3% MD-Transp.	43	3973	172			833	5089
0.3% MD-Domestic	6	3973	24			826	5113
PROCESS-EM. 60%	28	5000	144			798	5257
PROCESS-EM. 80%	19	8000	153			778	5411
.15% MD-Transp.	21	8669	187			757	5599
.15% MD-Domestic	3	8670	26			754	5626
RP Refineries	1	37315	59	445	784	752	5685
RP HF-Industry	0	40971	34	287	409	751	5719
RP HC-Industry	1	71642	108	769	1122	750	5828
RP DC-Industry	2	107684	239	1637	2388	747	6067
PROCESS-EM							

Poland pf -25%

_CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						4144	0
1.0% new HC-PP	17	533	9			4127	9
1.0% old HC-PP	192	533	102			3934	111
FGD Refineries	50	1092	55	194	784	3884	166
FGD new HFO-PP	8	1162	10	56	271	3875	177
1.0% HFO-Domest.	13	1201	16			3861	193
1.0% HF-Industry	16	1201	19			3845	213
1.0% old HFO-PP	100	1201	121			3744	334
FGD new HC-PP	162	1341	217	1081	5313	3582	552
FGD HF-Industry	9	1497	14	128	409	3572	566
FGD old HC-PP	1819	1709	3111	15782	59631	1753	3677
FGD new BC-PP	59	1777	105	1717	1911	1693	3783
FGD old HFO-PP	71	1832	131	1454	5345	1622	3914
PROCESS-EM. 30%	28	2000	57			1593	3972
FGD HC-Industry	48	2128	102	346	1122	1545	4074
FGD old BC-PP	487	2262	1102	18388	15734	1057	5177
FGD Cokeplants	111	2445	271	857	3546	946	5448
FGD DC-Industry	70	3068	215	736	2388	876	5664
0.3% MD-Transp.	43	3973	172			833	5837
0.3% MD-Domestic	6	3973	24			826	5861
PROCESS-EM. 60%	28	5000	144			798	6005
PROCESS-EM. 80%	19	8000	153			778	6159
.15% MD-Transp.	21	8669	187			757	6347
.15% MD-Domestic	3	8670	26			754	6374
RP Refineries	1	37315	59	445	784	752	6433
RP HF-Industry	0	40971	34	287	409	751	6467
RP HC-Industry	1	71642	108	769	1122	750	6576
RP DC-Industry	2	107684	239	1637	2388	747	6815
FGD HC-In							

Poland pf -50%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						4144	0
1.0% new HC-PP	17	533	9			4127	9
1.0% old HC-PP	192	533	102			3934	111
FGD Refineries	50	1092	55	194	784	3884	166
1.0% HFO-Domest.	13	1201	16			3870	183
1.0% HF-Industry	16	1201	19			3853	203
1.0% new HFO-PP	5	1201	6			3848	209
1.0% old HFO-PP	100	1201	121			3747	330
FGD HF-Industry	9	1497	14	128	409	3738	345
FGD new HC-PP	162	1960	317	1622	7970	3576	663
PROCESS-EM. 30%	28	2000	57			3547	720
FGD HC-Industry	48	2128	102	346	1122	3499	823
FGD new HFO-PP	3	2328	8	85	406	3495	831
FGD Cokeplants	111	2445	271	857	3546	3384	1103
FGD old HC-PP	1819	2513	4573	23673	89447	1565	5676
FGD new BC-PP	59	2590	153	2576	2866	1506	5829
FGD DC-Industry	70	3068	215	736	2388	1435	6045
FGD old BC-PP	487	3318	1618	27582	23601	948	7663
FGD old HFO-PP	71	3417	244	2181	8018	876	7908
0.3% MD-Transp.	43	3973	172			833	8081
0.3% MD-Domestic	6	3973	24			826	8105
PROCESS-EM. 60%	28	5000	144			798	8249
PROCESS-EM. 80%	19	8000	153			778	8403
.15% MD-Transp.	21	8669	187			757	8591
.15% MD-Domestic	3	8670	26			754	8618
RP Refineries	1	37315	59	445	784	752	8677
RP HF-Industry	0	40971	34	287	409	751	8711
RP HC-Industry	1	71642	108	769	1122	750	8820
RP DC-Industry	2	107684	239	1637	2388	747	9059

Poland pf -75%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						4144	0
1.0% new HC-PP	17	533	9			4127	9
1.0% old HC-PP	192	533	102			3934	111
FGD Refineries	50	1092	55	194	784	3884	166
1.0% HFO-Domest.	13	1201	16			3870	183
1.0% HF-Industry	16	1201	19			3853	203
1.0% new HFO-PP	5	1201	6			3848	209
1.0% old HFO-PP	100	1201	121			3747	330
FGD HF-Industry	9	1497	14	128	409	3738	345
PROCESS-EM. 30%	28	2000	57			3709	402
FGD HC-Industry	48	2128	102	346	1122	3661	505
FGD Cokeplants	111	2445	271	857	3546	3550	776
FGD DC-Industry	70	3068	215	736	2388	3479	992
FGD new HC-PP	162	3819	619	3245	15941	3317	1611
0.3% MD-Transp.	43	3973	172			3274	1784
0.3% MD-Domestic	6	3973	24			3268	1808
FGD old HC-PP	1819	4924	8960	47347	178894	1448	10769
PROCESS-EM. 60%	28	5000	144			1420	10913
FGD new BC-PP	59	5032	297	5153	5733	1360	11211
FGD new HFO-PP	3	5993	21	170	813	1357	11232
FGD old BC-PP	487	6487	3163	55164	47202	869	14396
PROCESS-EM. 80%	19	8000	153			850	14549
FGD old HFO-PP	71	8171	585	4363	16036	778	15135
.15% MD-Transp.	21	8669	187			757	15323
.15% MD-Domestic	3	8670	26			754	15349
RP Refineries	1	37315	59	445	784	752	15409
RP HF-Industry	0	40971	34	287	409	751	15443
RP HC-Industry	1	71642	108	769	1122	750	15552
RP DC-Industry	2	107684	239	1637	2388	747	15791

Poland sc 75%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest --Mill.DM--	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						4144	0
FGD new HFO-PP	17	494	8	42	203	4127	8
1.0% new HC-PP	159	533	85			3967	93
1.0% old HC-PP	1790	533	955			2177	1049
1.0% HC-Domestic	150	533	80			2026	1129
1.0% HC-Industry	24	533	12			2002	1142
FGD old HFO-PP	335	610	205	1090	4009	1666	1347
FGD new HC-PP	155	638	99	811	3985	1511	1446
FGD Refineries	88	648	57	194	784	1423	1504
FGD HF-Industry	46	772	35	128	409	1377	1539
1.0% DC-Domestic	34	796	27			1342	1567
1.0% DC-Industry	37	796	29			1305	1596
FGD new BC-PP	103	807	83	1288	1433	1201	1680
FGD old HC-PP	1739	927	1614	11836	44723	-537	3294
FGD old BC-PP	853	1015	866	13791	11800	-1391	4161
1.0% HFO-Domest.	30	1201	37			-1422	4198
FGD Cokeplants	194	1418	276	857	3546	-1616	4474
FGD HC-Industry	60	1515	91	346	1122	-1677	4566
PROCESS-EM. 30%	28	2000	57			-1706	4624
FGD DC-Industry	86	2200	189	736	2388	-1792	4813
0.3% MD-Domestic	15	3973	61			-1807	4875
0.3% MD-Transp.	108	3973	430			-1916	5305
PROCESS-EM. 60%	28	5000	144			-1944	5449
PROCESS-EM. 80%	19	8000	153			-1964	5603
.15% MD-Transp.	21	8669	187			-1985	5791
.15% MD-Domestic	3	8669	26			-1988	5818
RP Refineries	2	17978	50	445	784	-1991	5868
RP HF-Industry	1	20064	29	287	409	-1993	5897
RP HC-Industry	2	37457	99	769	1122	-1995	5997
RP DC-Industry	3	58218	226	1637	2388	-1999	6223

Poland sc 50%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest --Mill.DM--	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						4144	0
1.0% new HC-PP	111	533	59			4032	59
1.0% old HC-PP	1251	533	667			2781	727
1.0% HC-Domestic	32	533	17			2748	745
1.0% HC-Industry	11	533	5			2737	750
FGD new HFO-PP	14	568	8	42	203	2723	759
FGD old HFO-PP	287	703	202	1090	4009	2435	961
FGD Refineries	75	747	56	194	784	2359	1018
FGD new HC-PP	157	775	122	811	3985	2202	1140
1.0% DC-Domestic	17	796	13			2185	1153
1.0% DC-Industry	18	796	14			2166	1168
FGD HF-Industry	39	892	35	128	409	2127	1203
FGD new BC-PP	88	932	82	1288	1433	2038	1286
FGD old HC-PP	1766	1060	1872	11836	44723	271	3159
FGD old BC-PP	731	1175	859	13791	11800	-459	4018
1.0% HFO-Domest.	25	1201	30			-484	4049
FGD HC-Industry	61	1601	97	346	1122	-545	4146
FGD Cokeplants	167	1640	274	857	3546	-713	4421
PROCESS-EM. 30%	28	2000	57			-742	4479
FGD DC-Industry	87	2334	203	736	2388	-829	4682
0.3% MD-Transp.	86	3973	344			-915	5026
0.3% MD-Domestic	12	3973	49			-928	5076
PROCESS-EM. 60%	28	5000	144			-957	5220
PROCESS-EM. 80%	19	8000	153			-976	5373
.15% MD-Transp.	21	8669	187			-997	5561
.15% MD-Domestic	3	8669	26			-1001	5588
RP Refineries	2	22298	53	445	784	-1003	5641
RP HF-Industry	1	24735	30	287	409	-1004	5672
RP HC-Industry	2	45182	102	769	1122	-1006	5775
RP DC-Industry	3	69210	230	1637	2388	-1010	6006

Poland sc 25%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill	invest .DM--	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						5197	0
1.0% new HC-PP	65	533	34			5132	34
1.0% old HC-PP	731	533	390			4400	425
FGD new HFO-PP	12	669	8	42	203	4388	433
FGD old HFO-PP	240	831	199	1090	4009	4148	633
FGD Refineries	63	884	55	194	784	4085	688
FGD new HC-PP	159	903	144	811	3985	3925	833
FGD HF-Industry	32	1058	34	128	409	3892	868
FGD new BC-PP	74	1107	81	1288	1433	3818	949
FGD old HC-PP	1792	1183	2121	11836	44723	2026	3071
1.0% HFO-Domest.	19	1201	23			2006	3095
FGD old BC-PP	609	1398	852	13791	11800	1397	3947
FGD HC-Industry	60	1705	103	346	1122	1336	4050
FGD Cokeplants	138	1974	273	857	3546	1198	4323
PROCESS-EM. 30%	28	2000	57			1169	4381
FGD DC-Industry	87	2466	216	736	2388	1081	4598
0.3% MD-Transp.	65	3973	258			1016	4856
0.3% MD-Domestic	9	3973	37			1007	4893
PROCESS-EM. 60%	28	5000	144			978	5037
PROCESS-EM. 80%	19	8000	153			959	5191
.15% MD-Transp.	21	8670	187			937	5379
.15% MD-Domestic	3	8670	26			934	5405
RP Refineries	1	28247	56	445	784	932	5462
RP HF-Industry	1	31167	32	287	409	931	5494
RP HC-Industry	1	55442	105	769	1122	929	5600
RP DC-Industry	2	84599	234	1637	2388	926	5835
FGD HC-In							
FGD Cokep							
PROCESS-EM							

Poland sc 10%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill	invest .DM--	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						4573	0
1.0% new HC-PP	36	533	19			4537	19
1.0% old HC-PP	404	533	215			4132	235
FGD new HFO-PP	10	753	8	42	203	4122	243
FGD old HFO-PP	210	938	197	1090	4009	3911	441
FGD new HC-PP	161	981	158	811	3985	3750	599
FGD Refineries	55	998	55	194	784	3694	654
FGD HF-Industry	28	1196	34	128	409	3665	689
1.0% HFO-Domest.	16	1201	19			3649	708
FGD new BC-PP	65	1250	81	1288	1433	3584	790
FGD old HC-PP	1808	1259	2278	11836	44723	1775	3068
FGD old BC-PP	536	1581	848	13791	11800	1239	3916
FGD HC-Industry	53	1935	102	346	1122	1186	4019
PROCESS-EM. 30%	28	2000	57			1157	4076
FGD Cokeplants	122	2217	272	857	3546	1035	4349
FGD DC-Industry	77	2795	216	736	2388	957	4565
0.3% MD-Transp.	52	3973	206			905	4772
0.3% MD-Domestic	7	3973	29			898	4801
PROCESS-EM. 60%	28	5000	144			869	4945
PROCESS-EM. 80%	19	8000	153			850	5099
.15% MD-Transp.	21	8670	187			828	5287
.15% MD-Domestic	3	8670	26			825	5314
RP Refineries	1	33219	58	445	784	823	5372
RP HF-Industry	0	36543	33	287	409	822	5405
RP HC-Industry	1	64258	107	769	1122	821	5513
RP DC-Industry	2	97191	237	1637	2388	818	5750
FGD HC-In							
PROCESS-EM							
FGD Cokep							

Poland sc 1%

_CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						4212	0
1.0% new HC-PP	18	533	10			4193	10
1.0% old HC-PP	211	533	113			3982	123
FGD new HFO-PP	9	814	8	42	203	3972	131
FGD old HFO-PP	194	1015	197	1090	4009	3778	328
FGD new HC-PP	162	1027	166	811	3985	3616	494
FGD Refineries	50	1080	55	194	784	3565	549
1.0% HFO-Domest.	14	1201	16			3551	566
1.0% HF-Industry	16	1201	20			3534	586
FGD old HC-PP	1818	1303	2370	11836	44723	1715	2957
FGD new BC-PP	60	1348	81	1288	1433	1655	3038
FGD HF-Industry	9	1460	14	128	409	1645	3052
FGD old BC-PP	495	1706	845	13791	11800	1150	3898
PROCESS-EM. 30%	28	2000	57			1121	3956
FGD HC-Industry	48	2102	102	346	1122	1072	4058
FGD Cokeplants	112	2404	271	857	3546	959	4330
FGD DC-Industry	71	3031	215	736	2388	888	4546
0.3% MD-Domestic	6	3973	25			882	4571
0.3% MD-Transp.	44	3973	177			837	4749
PROCESS-EM. 60%	28	5000	144			808	4893
PROCESS-EM. 80%	19	8000	153			789	5047
.15% MD-Transp.	21	8669	187			767	5235
.15% MD-Domestic	3	8670	26			764	5262
RP Refineries	1	36781	59	445	784	762	5321
RP HF-Industry	0	40393	33	287	409	762	5355
RP HC-Industry	1	70637	108	769	1122	760	5464
RP DC-Industry	2	106259	239	1637	2388	758	5703
PROCESS-EM							
FGD HC-In							

Poland sc -1%

_CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						4119	0
1.0% new HC-PP	15	533	8			4104	8
1.0% old HC-PP	173	533	92			3931	100
FGD new HFO-PP	9	829	8	42	203	3921	108
FGD old HFO-PP	190	1034	196	1090	4009	3731	305
FGD new HC-PP	162	1036	168	811	3985	3569	473
FGD Refineries	49	1101	55	194	784	3519	528
1.0% HF-Industry	16	1201	19			3502	548
1.0% HFO-Domest.	13	1201	16			3489	564
FGD old HC-PP	1820	1312	2389	11836	44723	1668	2953
FGD new BC-PP	58	1392	81	1288	1433	1610	3034
FGD HF-Industry	9	1521	14	128	409	1600	3049
FGD old BC-PP	479	1762	845	13791	11800	1121	3894
PROCESS-EM. 30%	28	2000	57			1092	3952
FGD HC-Industry	47	2155	102	346	1122	1045	4054
FGD Cokeplants	109	2487	271	857	3546	936	4325
FGD DC-Industry	69	3106	215	736	2388	866	4541
0.3% MD-Transp.	41	3973	166			824	4708
0.3% MD-Domestic	6	3973	23			818	4732
PROCESS-EM. 60%	28	5000	144			789	4876
PROCESS-EM. 80%	19	8000	153			770	5029
.15% MD-Transp.	21	8669	187			748	5217
.15% MD-Domestic	3	8669	26			745	5244
RP Refineries	1	37678	59	445	784	744	5304
RP HF-Industry	0	41364	34	287	409	743	5338
RP HC-Industry	1	72673	108	769	1122	741	5447
RP DC-Industry	2	109145	239	1637	2388	739	5686
PROCESS-EM							
FGD HC-In							

Poland sc -10%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						3757	0
FGD new HFO-PP	8	908	7	42	203	3749	7
FGD new HC-PP	161	1086	175	811	3985	3587	183
FGD old HFO-PP	172	1134	195	1090	4009	3415	379
1.0% HFO-Domest.	11	1201	13			3403	392
1.0% HF-Industry	13	1201	16			3389	409
FGD Refineries	45	1207	54	194	784	3344	464
FGD old HC-PP	1810	1364	2471	11836	44723	1533	2935
FGD new BC-PP	53	1516	80	1288	1433	1480	3016
FGD HF-Industry	9	1799	17	128	409	1470	3033
FGD old BC-PP	438	1920	842	13791	11800	1031	3876
PROCESS-EM. 30%	28	2000	57			1003	3934
FGD HC-Industry	43	2365	102	346	1122	960	4036
FGD Cokeplants	99	2726	270	857	3546	860	4307
FGD DC-Industry	63	3403	215	736	2388	797	4522
0.3% MD-Transp.	34	3973	137			762	4660
0.3% MD-Domestic	4	3973	19			757	4680
PROCESS-EM. 60%	28	5000	144			728	4824
PROCESS-EM. 80%	19	8000	153			709	4977
.15% MD-Transp.	21	8669	187			688	5165
.15% MD-Domestic	3	8669	26			684	5192
RP Refineries	1	42321	60	445	784	683	5253
RP HF-Industry	0	46383	34	287	409	682	5287
RP HC-Industry	1	80714	110	769	1122	681	5397
RP DC-Industry	1	120508	240	1637	2388	679	5638
PROCESS-EM							
FGD HC-In							
FGD Cokep							
FGD DC-In							

Poland sc -25%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						3163	0
FGD new HFO-PP	7	1076	7	42	203	3156	7
1.0% HFO-Domest.	8	1201	9			3148	17
1.0% HF-Industry	9	1201	11			3138	29
1.0% old HFO-PP	71	1201	85			3067	114
FGD new HC-PP	135	1285	173	811	3985	2932	288
FGD Refineries	37	1434	54	194	784	2894	342
FGD old HFO-PP	73	1487	108	1090	4009	2820	451
FGD old HC-PP	1518	1616	2454	11836	44723	1302	2905
FGD new BC-PP	44	1807	80	1288	1433	1258	2986
PROCESS-EM. 30%	28	2000	57			1229	3043
FGD HF-Industry	10	2230	22	128	409	1219	3066
FGD old BC-PP	365	2292	838	13791	11800	854	3904
FGD HC-Industry	36	2795	101	346	1122	817	4006
FGD Cokeplants	83	3222	269	857	3546	733	4276
0.3% MD-Transp.	21	3973	86			712	4362
0.3% MD-Domestic	3	3973	12			709	4374
FGD DC-Industry	52	4072	214	736	2388	656	4589
PROCESS-EM. 60%	28	5000	144			627	4733
PROCESS-EM. 80%	19	8000	153			608	4887
.15% MD-Domestic	3	8670	26			605	4914
.15% MD-Transp.	21	8670	187			583	5102
RP Refineries	1	52173	62	445	784	582	5164
RP HF-Industry	0	57034	35	287	409	581	5200
RP HC-Industry	1	97205	111	769	1122	580	5311
RP DC-Industry	1	146157	243	1637	2388	578	5555
FGD old B							
FGD HC-In							
FGD Cokep							

Poland sc -50%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest --Mill.DM--	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						2131	0
1.0% new HFO-PP	1	1201	1			2130	1
1.0% HFO-Domest.	2	1201	2			2128	3
1.0% HF-Industry	2	1201	3			2125	7
1.0% old HFO-PP	20	1201	24			2105	31
FGD new HFO-PP	3	1692	6	42	203	2101	38
FGD new HC-PP	89	1910	171	811	3985	2012	209
PROCESS-EM. 30%	28	2000	57			1983	266
FGD Refineries	25	2128	53	194	784	1958	320
FGD old HFO-PP	75	2208	167	1090	4009	1882	487
FGD old HC-PP	1005	2410	2424	11836	44723	876	2912
FGD new BC-PP	29	2682	79	1288	1433	846	2991
FGD HF-Industry	10	2926	30	128	409	836	3022
FGD old BC-PP	243	3410	831	13791	11800	592	3853
FGD HC-Industry	24	4199	100	346	1122	568	3954
FGD Cokeplants	56	4750	268	857	3546	512	4223
PROCESS-EM. 60%	28	5000	144			483	4367
FGD DC-Industry	35	6080	213	736	2388	448	4581
PROCESS-EM. 80%	19	8000	153			428	4734
RP Refineries	0	82367	65	445	784	428	4800
RP HF-Industry	0	89679	37	287	409	427	4837
RP HC-Industry	0	151021	114	769	1122	426	4952
RP DC-Industry	1	223104	247	1637	2388	425	5199
FGD old H							
FGD old H							
FGD new B							
FGD HF-In							
FGD old B							
FGD HC-In							

Poland sc -75%

CONTROL OPTION	SO2 remov. (kt)	spec. costs DM/t SO2	annual costs --Mill.DM--	invest --Mill.DM--	inst. capac. MW	remain. SO2 (kt)	total annual costs
Unabated SO2						1127	0
PROCESS-EM. 30%	28	2000	57			1098	57
FGD new HFO-PP	2	3097	7	42	203	1096	65
FGD new HC-PP	45	3697	168	811	3985	1050	233
FGD old HFO-PP	48	3904	188	1090	4009	1002	422
FGD Refineries	12	4166	52	194	784	989	475
FGD old HC-PP	512	4679	2396	11836	44723	477	2871
PROCESS-EM. 60%	28	5000	144			448	3015
FGD HF-Industry	6	5029	33	128	409	442	3049
FGD new BC-PP	14	5308	78	1288	1433	427	3127
FGD old BC-PP	121	6763	824	13791	11800	305	3952
PROCESS-EM. 80%	19	8000	153			286	4105
FGD HC-Industry	12	8134	100	346	1122	273	4206
FGD Cokeplants	27	9779	266	857	3546	246	4472
FGD DC-Industry	17	12102	212	736	2388	229	4685
RP Refineries	0	171041	68	445	784	228	4754
RP HF-Industry	0	185549	38	287	409	228	4793
RP HC-Industry	0	301842	117	769	1122	228	4910
RP DC-Industry	0	453945	252	1637	2388	227	5162
FGD Refin							
FGD old H							
PROCESS-EM							
FGD HF-In							
FGD new B							
FGD old B							
PROCESS-EM							
FGD HC-In							
FGD Cokep							
FGD DC-In							

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Lene Sørensen

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Abstract (Max. 2000 characters)

This report addresses the problems concerning evaluation of Integrated Environmental Models. The RAINS model developed at the International Institute for Applied Systems Analysis, Laxenburg, Austria is presented and analyzed as one example on an Integrated Environmental Model.

A sensitivity analysis was applied to parts of the RAINS model. This analysis focused on the socalled cost part of the model where economic considerations on emission reductions are sought described.

The report ends suggesting a number of criteria to base the evaluation of Integrated Environmental Models' usability on. These criteria widen the traditional evaluation concept and considers concepts as robustness, accuracy, simplicity, adequacy, transparency, and effectiveness. The criteria are concretisized by applying them to the RAINS model.

The report represents the third part of the Ph.D. thesis on Environmental Planning and Uncertainty.

Descriptors INIS/EDB

COST; DATA COVARIANCES; DECISION MAKING; EMISSION; ENVIRONMENTAL IMPACTS; ENVIRONMENTAL POLICY; EVALUATION; MATHEMATICAL MODELS; NUMERICAL DATA; PLANNING; SENSITIVITY ANALYSIS; SYSTEMS ANALYSIS

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